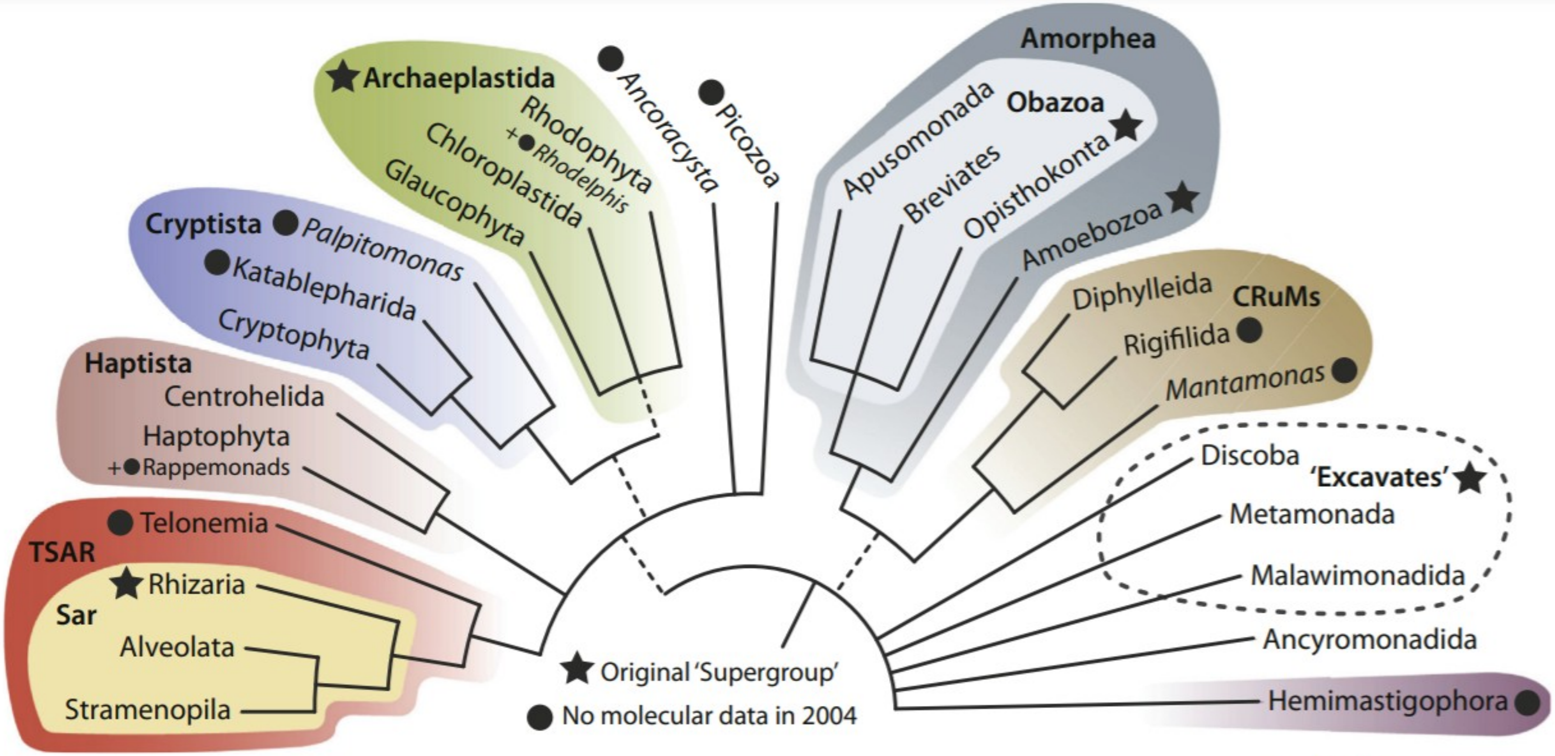


Trends in Ecology & Evolution

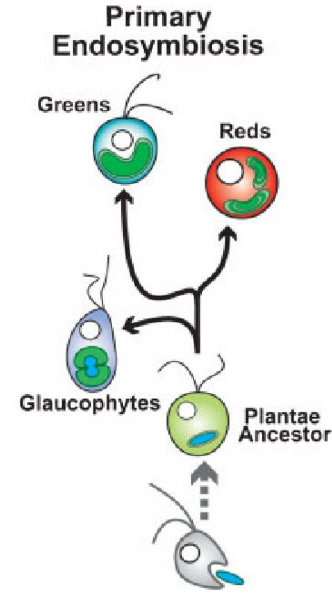
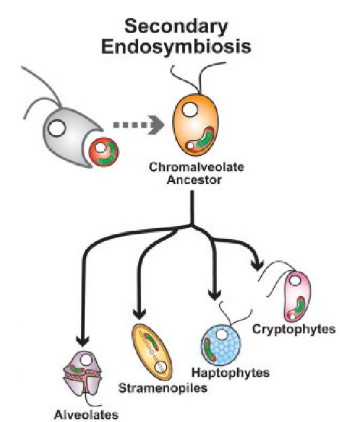


Figure 1. The New Tree of Eukaryotes.

This summary is based on a consensus of recent phylogenomic studies. The colored groupings correspond to the current 'supergroups'. Unresolved branching orders among lineages are shown as multifurcations. Broken lines reflect lesser uncertainties about the monophyly of certain groups. Star symbols denote taxa that were considered as supergroups in early versions of the supergroup model; thus, all original supergroups except Archaeplastida have either disappeared or been subsumed into new taxa. The circles show major lineages that had no molecular data when the supergroup model emerged, most often because they had not yet been discovered. Rappemonads (in parentheses) are placed on the basis of plastid rRNA data only. The putative new major lineages *Microheliella* and *Anaeramoeba* are not shown due to the limited evidence that they belong outside all existing groups shown here (Table 1).



Burki et al., 2020, Trend Ecol Evol

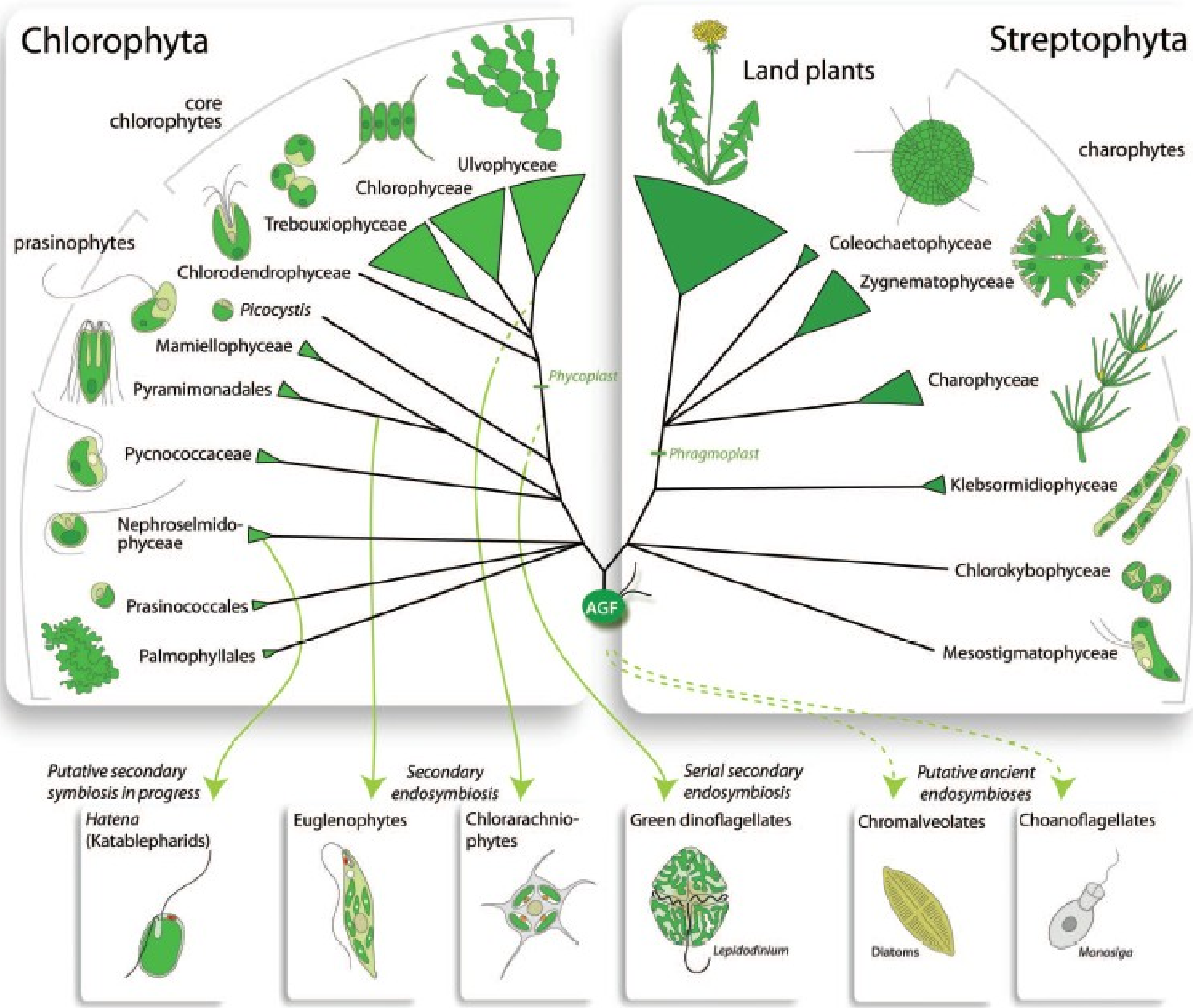
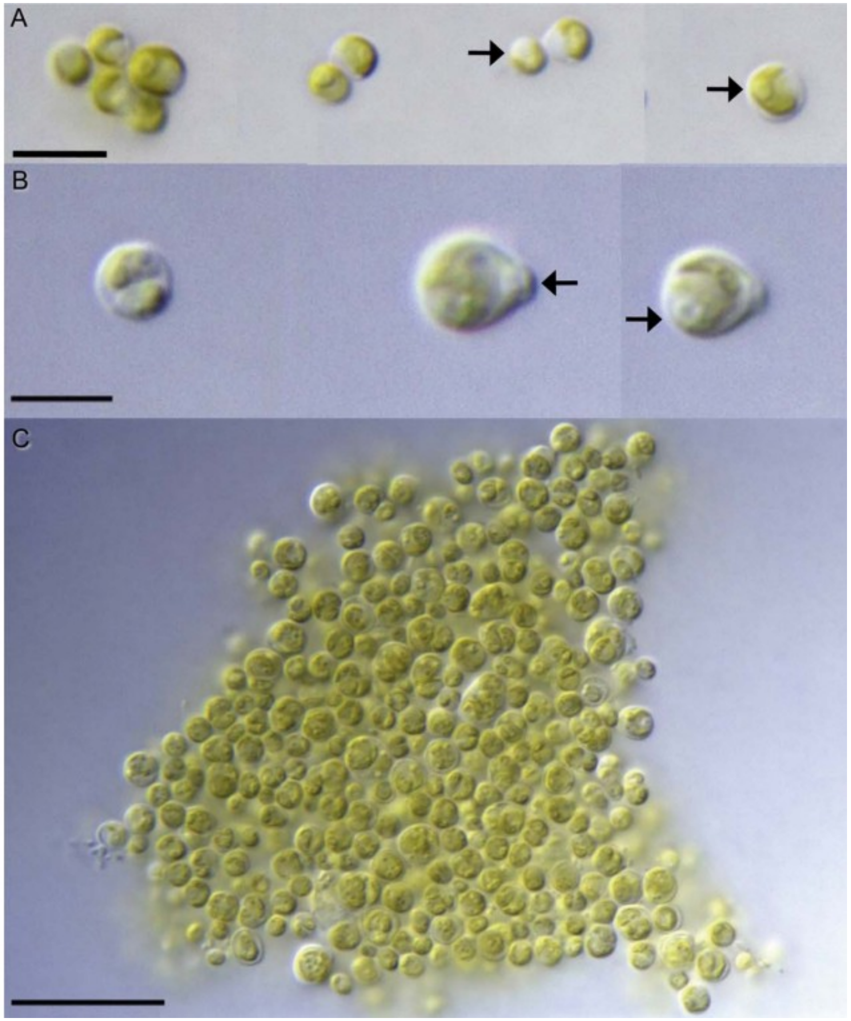


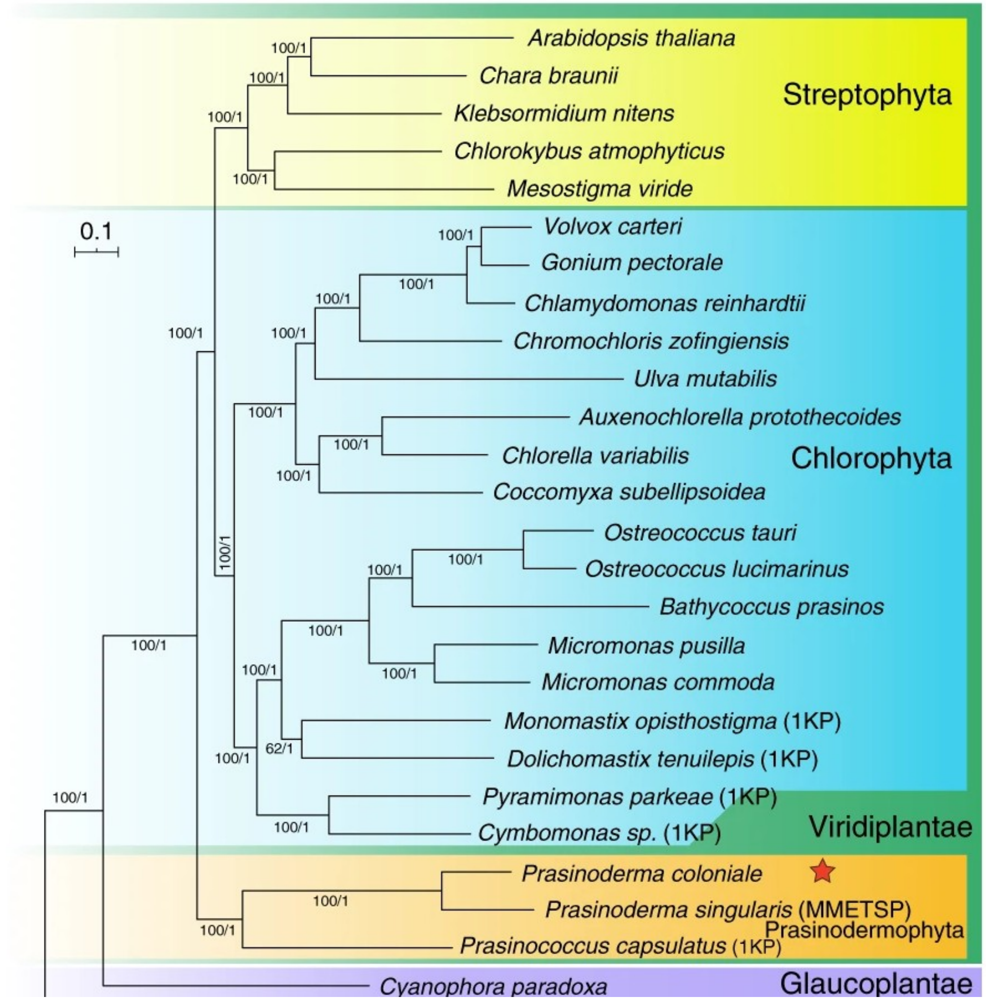
FIG. 2. Overview phylogeny of the green lineage (top) and spread of green genes in other eukaryotes (bottom). (Color figure available online.)

Leliaert et al., 2012, Crit. Rev. Pl. Sci. 31: 1-46

Prasinodermatophyta

the third lineage of Viridiplantae



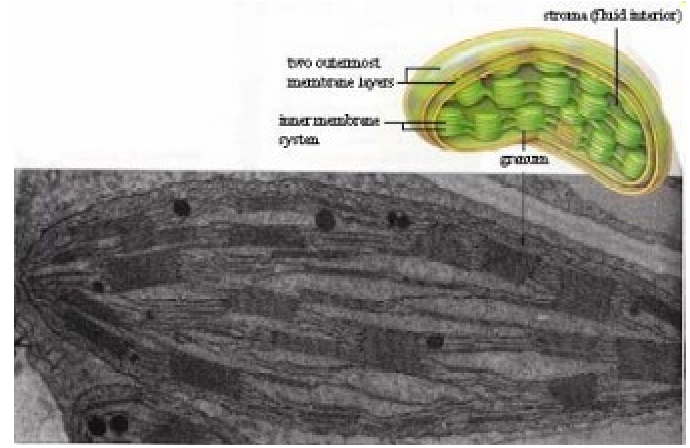


oceanic picoplankton (warm watr regions)

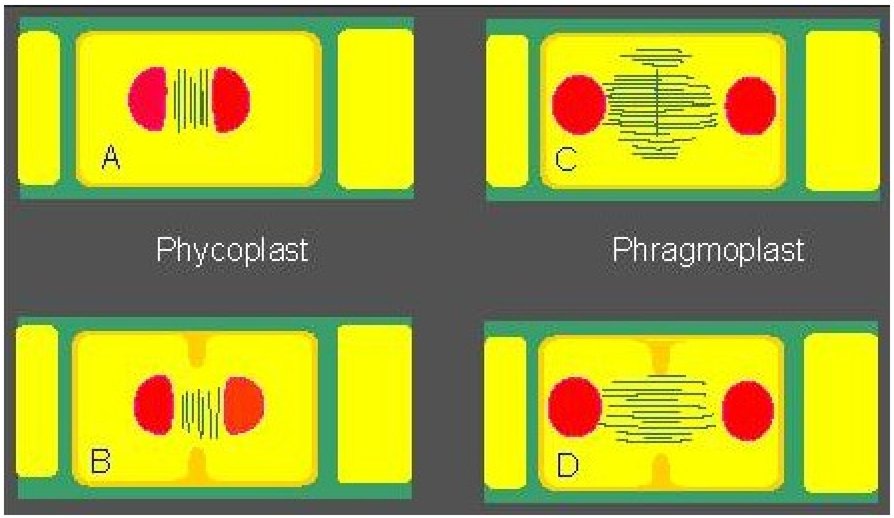
Li et al., 2020, Nat Ecol Evol

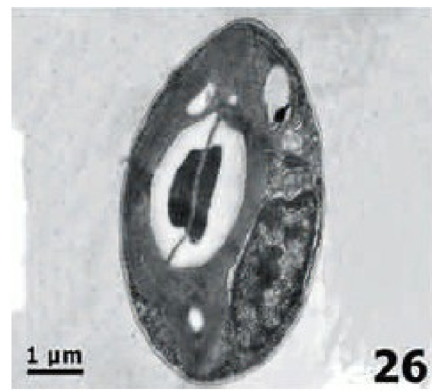
Jouenne et al., 2011, Protist

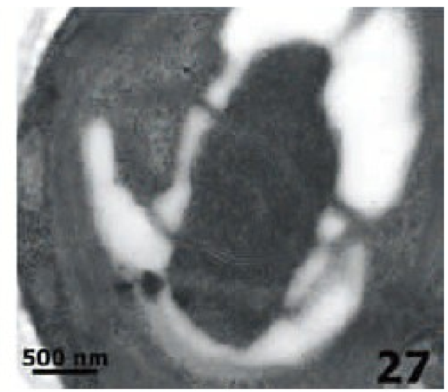
<u>Kingdom</u>: plants – *Plantae (= Archaepastida)*
<u>Infrakingdom</u>: ***Viridiplantae* – green plants**

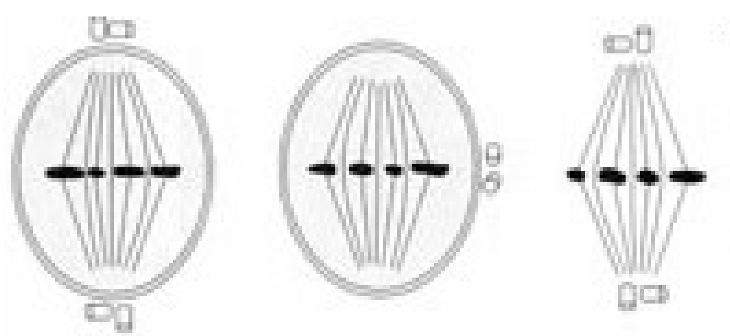


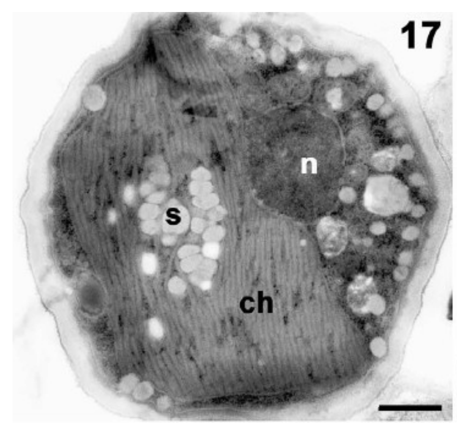
two evolutionary lineages- *Chlorophyta* a *Streptophyta*

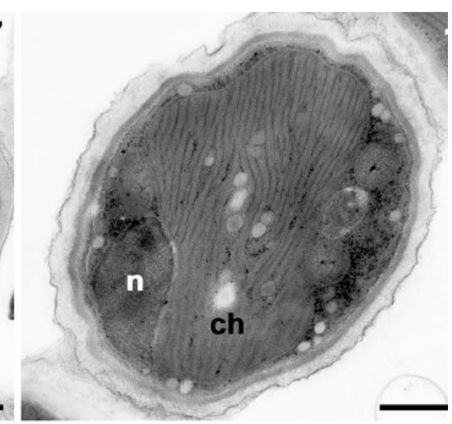












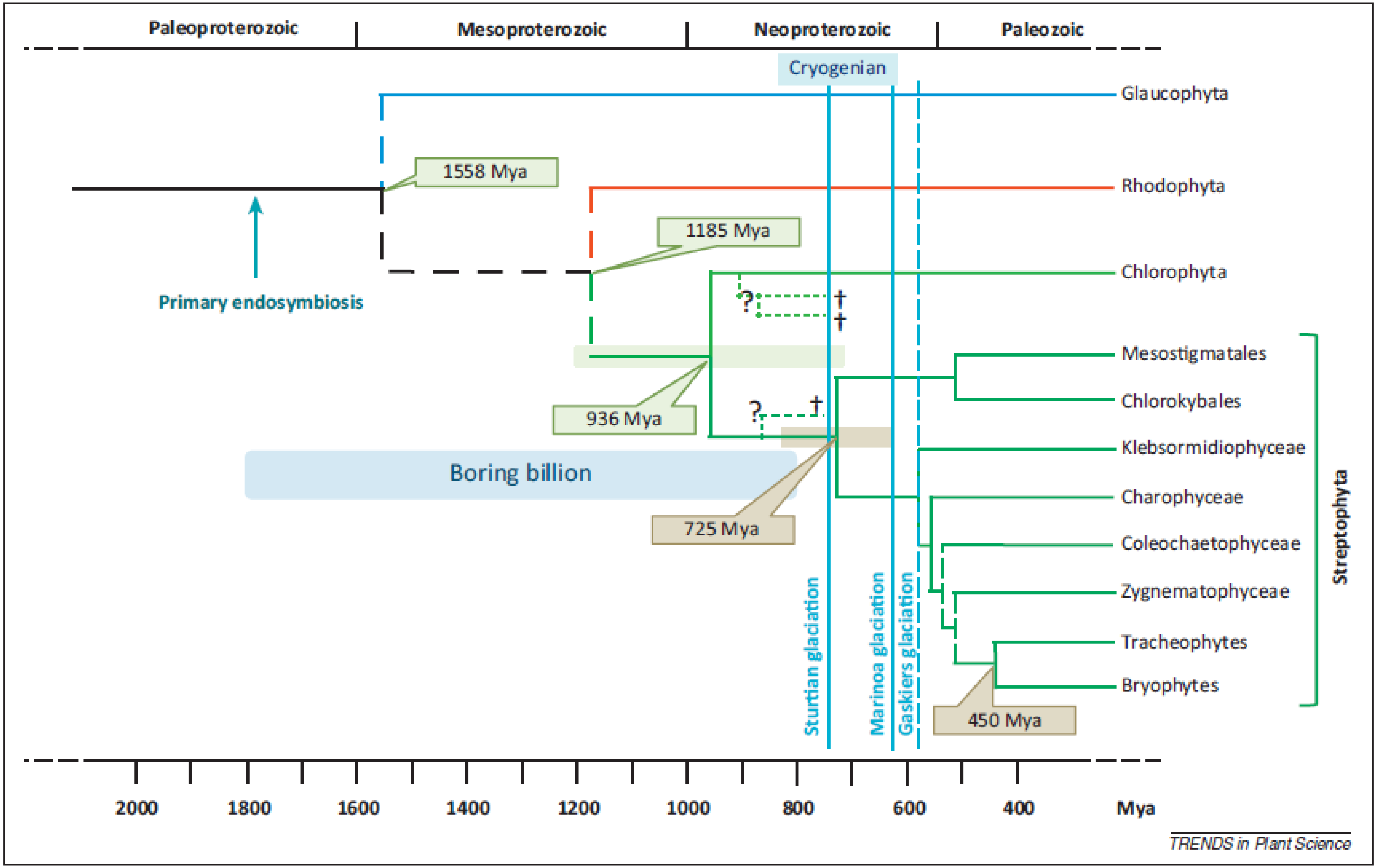


Figure 2. Plant evolution and major glaciation events. The scheme illustrates the evolution of plants. The streptophyte tree topology is based on [15,16]. Dashed lines indicate uncertain relationships. Nodes are dated according to TIMETREE (primary plastid groups, greenish boxed dates) or [25] (brownish boxed dates). The observed variation of divergence time estimates for chlorophytes and streptophytes is indicated with a greenish box, and the highest-probability density range given by [25] for the Mesostigma/other streptophytes split with a brownish box. The primary endosymbiosis is indicated by a vertical arrow. Today, extinct possible streptophyte and chlorophyte branches are marked with a question mark and terminate with a cross. Blue vertical lines indicate hard and soft (dashed line) snow ball states of the earth. The date for glaciation events and the boring billion period are based on [30]. The time frame for the Cryogenian period indicated is based on [36].

Becker, 2012, TRPLSC

Evolution of green plant lineage

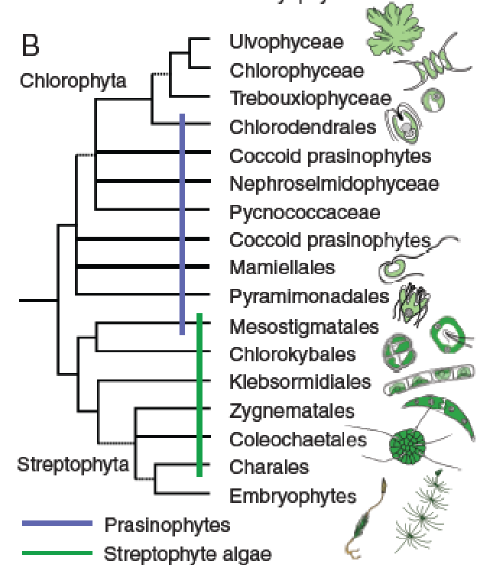
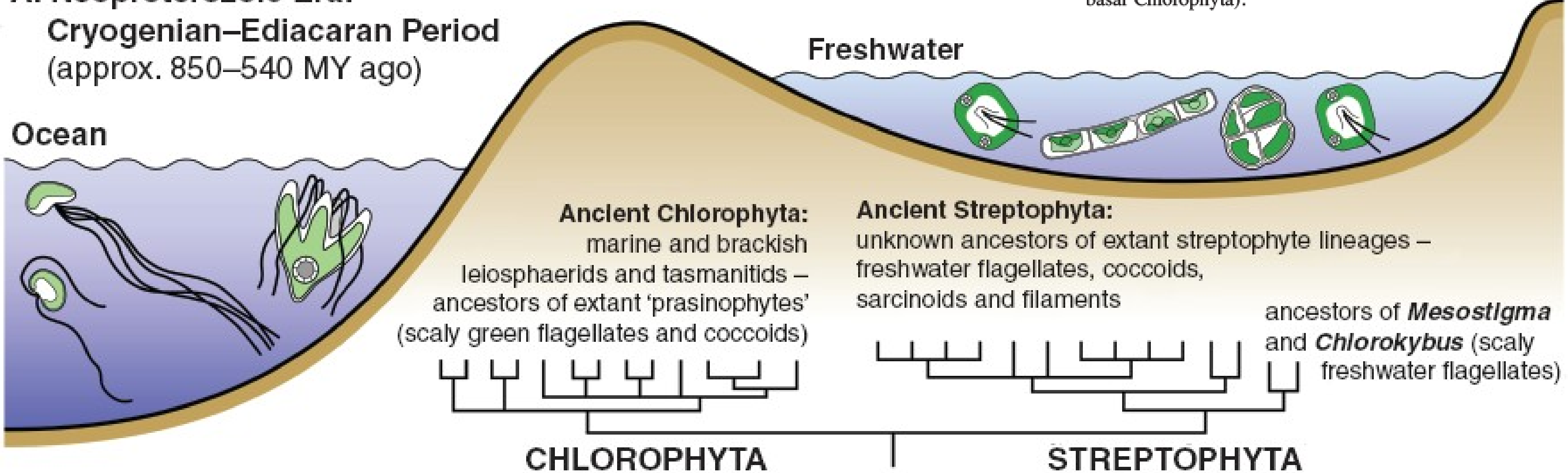
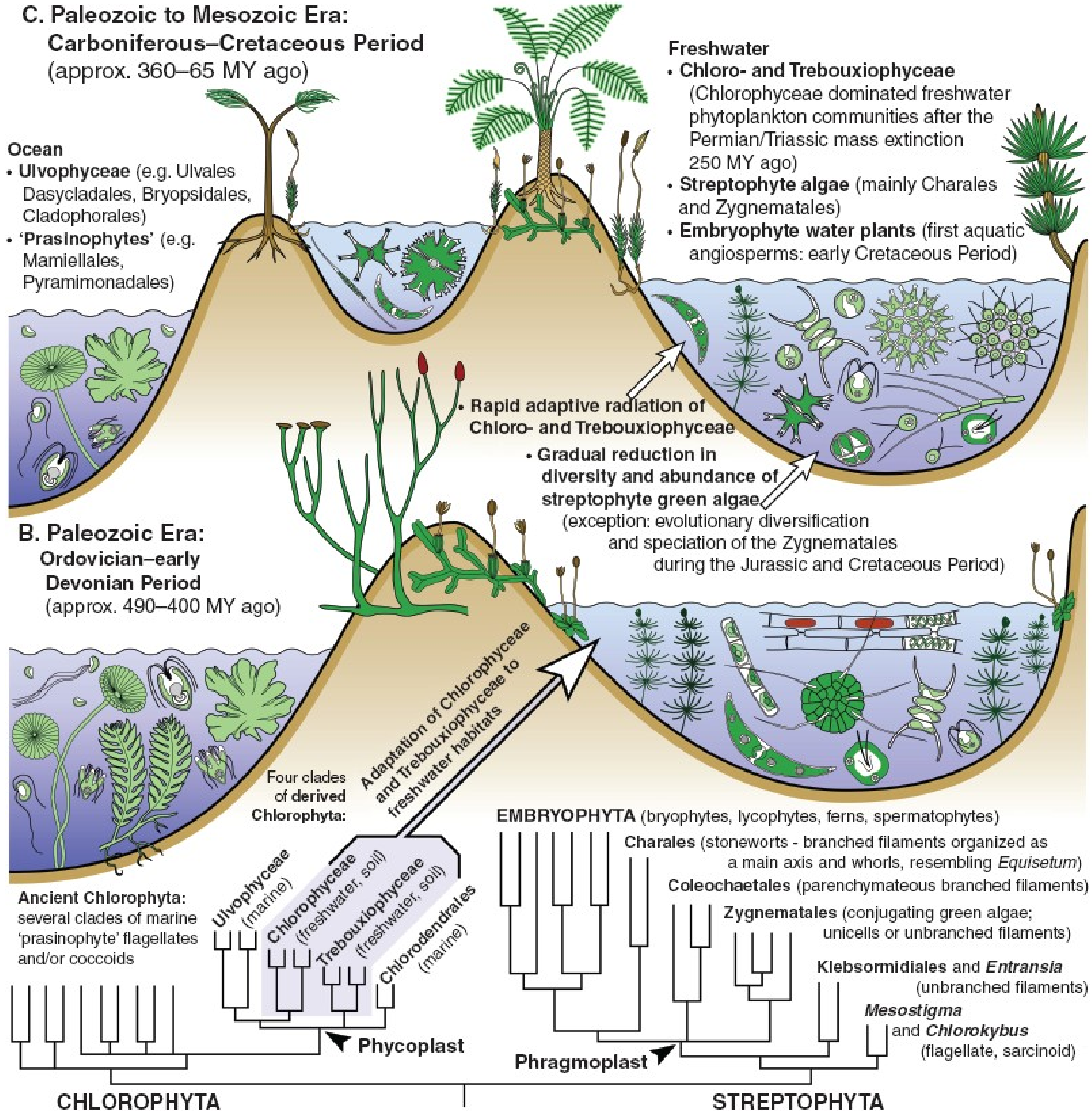


FIG. 1. Phylogenetic relationships among the major lineages of the Viridiplantae. Branches indicated by dotted lines are not well supported. (A) According to Lewis and McCourt (2004), and (B) based on unpublished, ongoing work by the authors. Some of the class names used by Lewis and McCourt (2004) have never been validly described, and for this reason we use order designations in (B) and throughout the text. The informal term 'prasinophytes' is commonly used for scaly green flagellates (Mesostigmatales and basal Chlorophyta).

A. Neoproterozoic Era:

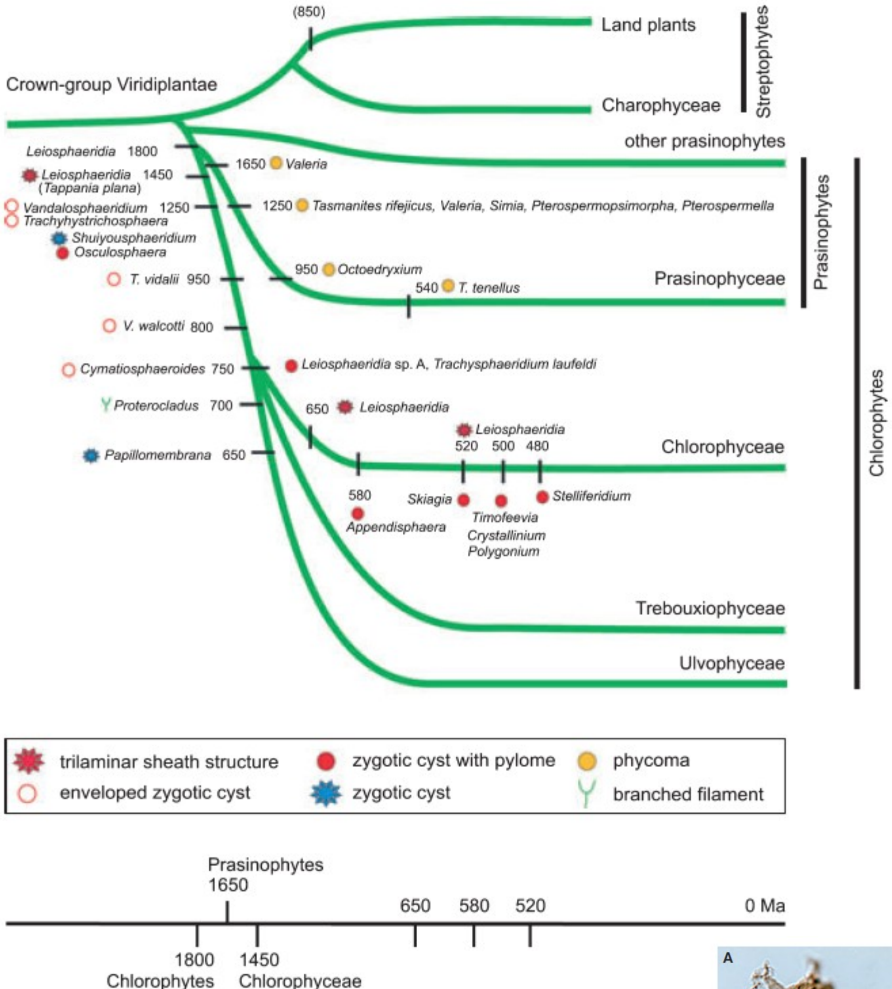


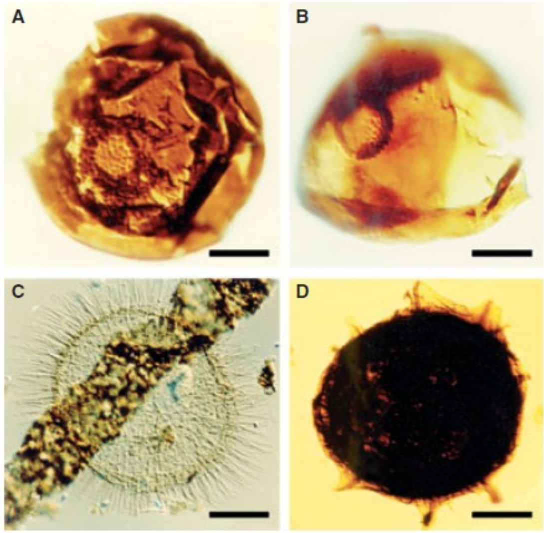
Becker & Marin, 2009, Ann Bot 103: 999-1004



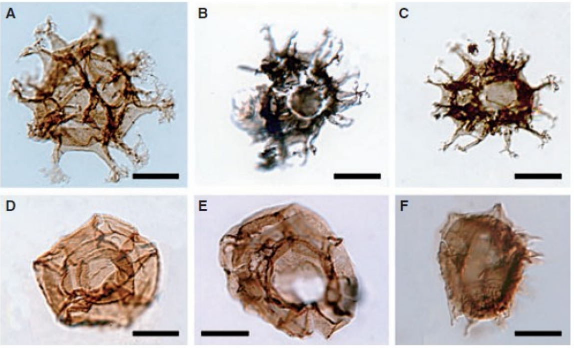
C. Paleozoic to Mesozoic Era:
Carboniferous–Cretaceous Period
(approx. 360–65 MY ago)
Ocean
• Ulvophyceae (e.g. Ulvales Dasycladales, Bryopsidales, Cladophorales)
• 'Prasinophytes' (e.g. Mamiellales, Pyramimonadales)
Freshwater
• Chloro- and Trebouxiophyceae (Chlorophyceae dominated freshwater phytoplankton communities after the Permian/Triassic mass extinction 250 MY ago)
• Streptophyte algae (mainly Charales and Zygnematales)
• Embryophyte water plants (first aquatic angiosperms: early Cretaceous Period)
• Rapid adaptive radiation of Chloro- and Trebouxiophyceae
• Gradual reduction in diversity and abundance of streptophyte green algae (exception: evolutionary diversification and speciation of the Zygnematales during the Jurassic and Cretaceous Period)
B. Paleozoic Era:
Ordovician–early Devonian Period
(approx. 490–400 MY ago)
Adaptation of Chlorophyceae and Trebouxiophyceae to freshwater habitats
Four clades of derived Chlorophyta:
Ulvophyceae (marine)
Chlorophyceae (freshwater, soil)
Trebouxiophyceae (freshwater, soil)
Chlorodendrales (marine)
Ancient Chlorophyta: several clades of marine 'prasinophyte' flagellates and/or coccoids
Phycoplast
EMBRYOPHYTA (bryophytes, lycophytes, ferns, spermatophytes)
Charales (stoneworts - branched filaments organized as a main axis and whorls, resembling Equisetum)
Coleochaetales (parenchymateous branched filaments)
Zygnematales (conjugating green algae; unicells or unbranched filaments)
Klebsormidiales and Entransia (unbranched filaments)
Mesostigma and Chlorokybus (flagellate, sarcinoid)
Phragmoplast
CHLOROPHYTA
STREPTOPHYTA

TEXT-FIG. 4. Phylogeny of the Viridiplantae (modified from O'Kelly 2007 and Moustafa *et al.* 2009). The chronologically arranged, earliest appearance of microfossils interpreted to be green microalgae constrains the origin of the classes Prasinophyceae, Chlorophyceae and Ulvophyceae. The first appearance data of the microfossils are compiled from sources cited in the text. Terrestrial expansion of biota at *c.* 850 Ma is according to Knauth and Kennedy (2009). The time axis is drawn not in scale and shows the time of the origins of the Chlorophytes prior to *c.* 1800 Ma, Prasinophyceae *c.* 1650 Ma, Chlorophyceae *c.* 1450 Ma, and major radiations of phytoplankton at *c.* 650, 580 and 520 Ma.





TEXT-FIG. 1. Neoproterozoic microfossils. A, B. *Leiosphaeridia* sp. A, with pylome. Chuar Group, the Great Canyon, northern Arizona (Cryogenian). A, Specimen LO 5658. B, Specimen LO 5659. C, *Appendisphaera grandis*. Khamaka Fromation, eastern Siberia (Ediacaran). Specimen PMU-Sib.1-L/27/1. D, *Trachyhystrichosphaera vidalii*. Khajpakh Foramtion, eastern Siberia (Tonian). Specimen PMU-Sib.6-N/43/3. Scale bars represent 10 μm for A, 7 μm for B, 38 μm for C and 46 μm for D. All are light photomicrographs.

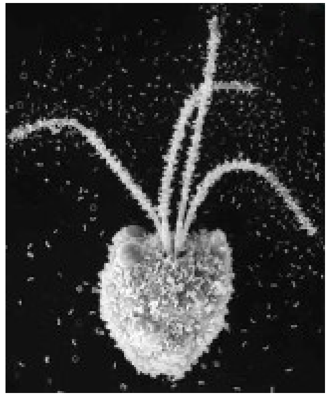


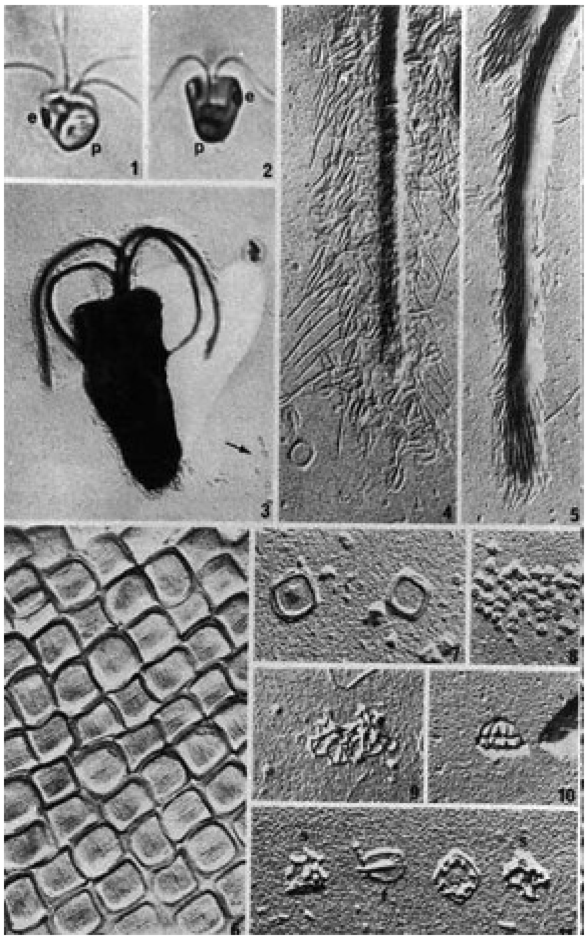
TEXT-FIG. 3. Cambrian microfossils. A–C. *Timofeevia lancare*. A, Immature stage, specimen SP-2009.10.A/10. B, Specimen with ontogenetically defined pylome, ZL05-13b-L/43. C, Specimen with opened pylome, ZL05-13-G/20/4. D–E, *Cristallinium cambriense*. D, Specimen in immature stage, SP-2009.11.C/15/2. E, Specimen with two open pylomes, SP-2009-12.V/16. F, *Polygonium varium* containing the endocyst, specimen PO106-11N2-A/15/4. Specimens A, D–F, Oville Formation, Cantabrian Mountains, northern Spain; specimens B, C, Playón Formation, Ossa-Morena Zone, central Spain. Scale bars represent 15 μm for all specimens.

Moczydlowska et al, 2011, Palaeontology 54

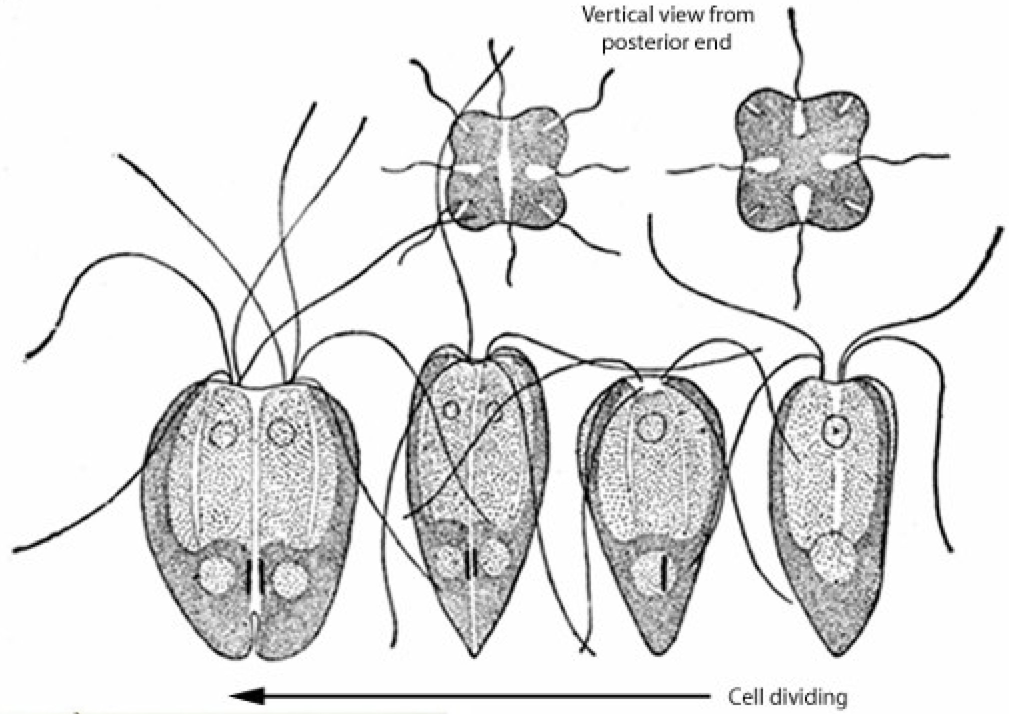
Prasinophyceae

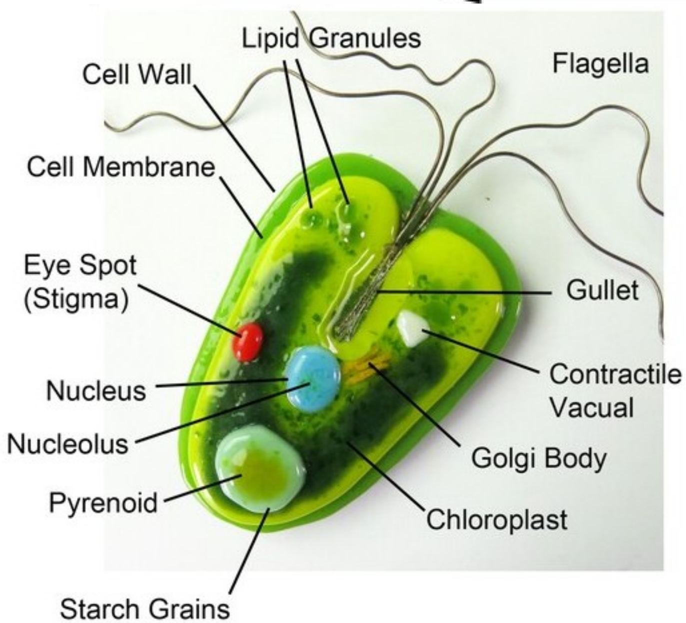
Pyramimonas



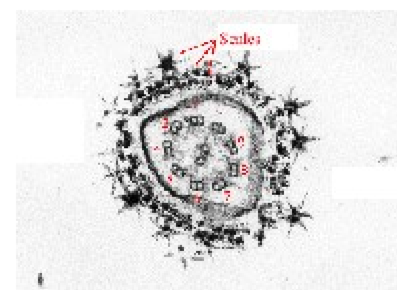


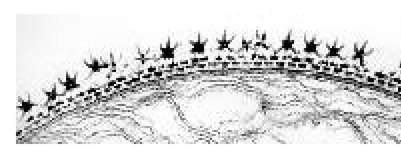
Pyramimonas





source: etsy.com

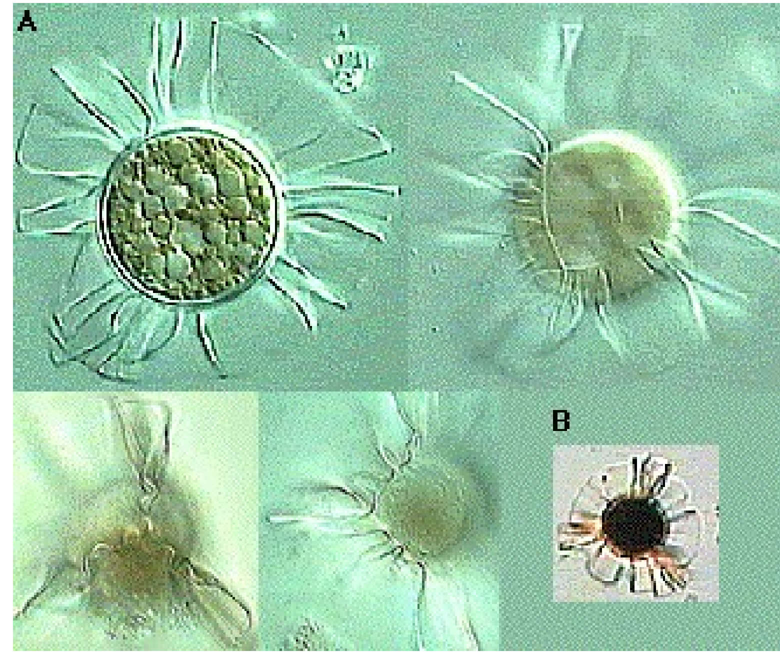


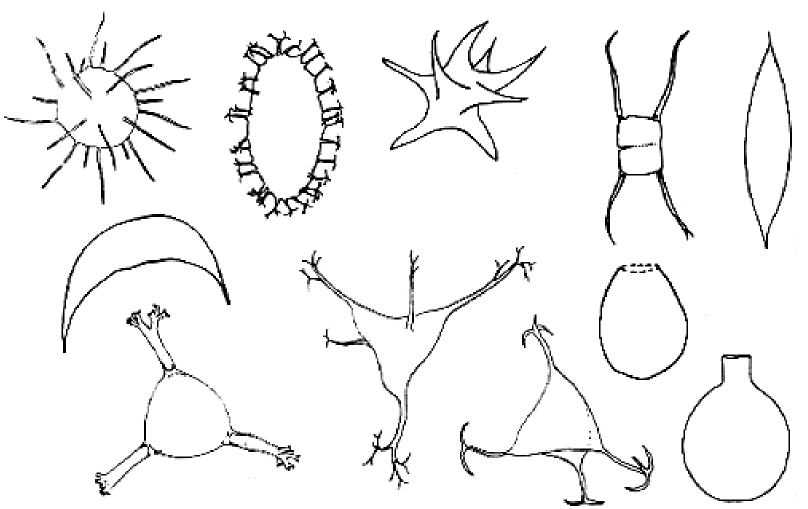


Freshwater and marine flagellates

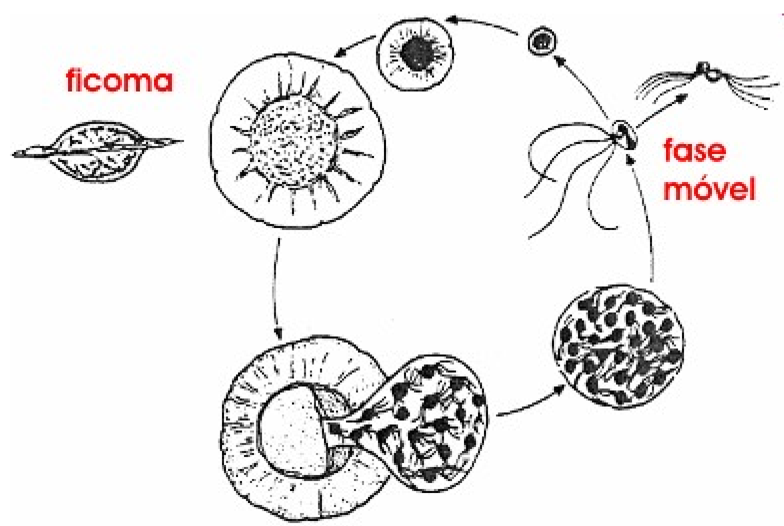
Prasinophyceae

Pterosperma



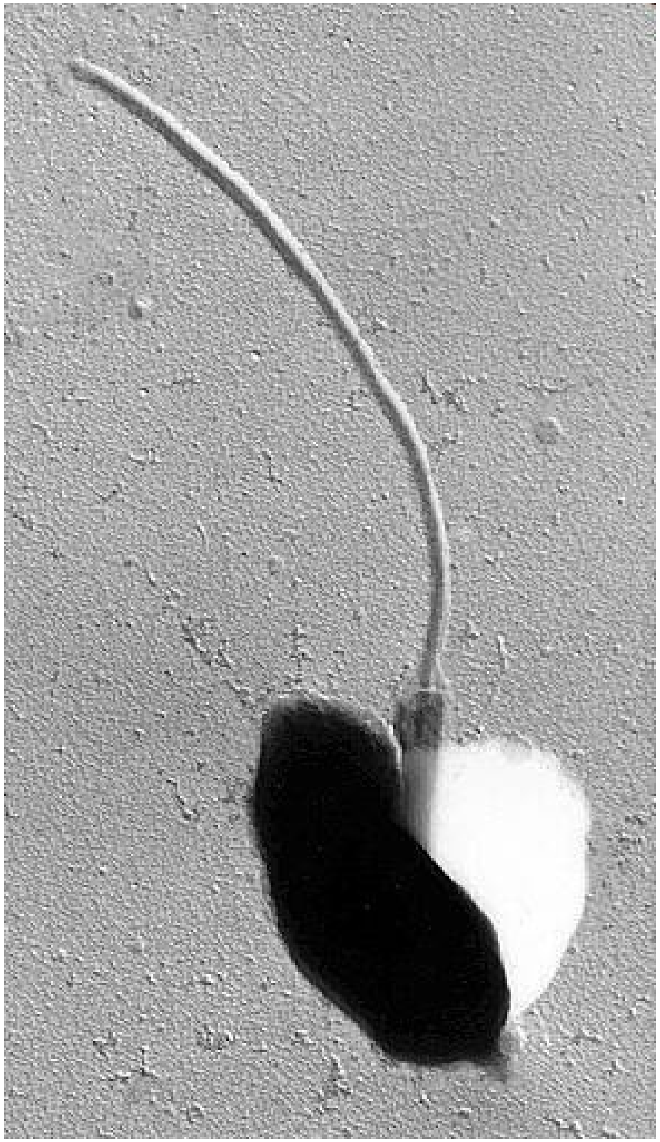


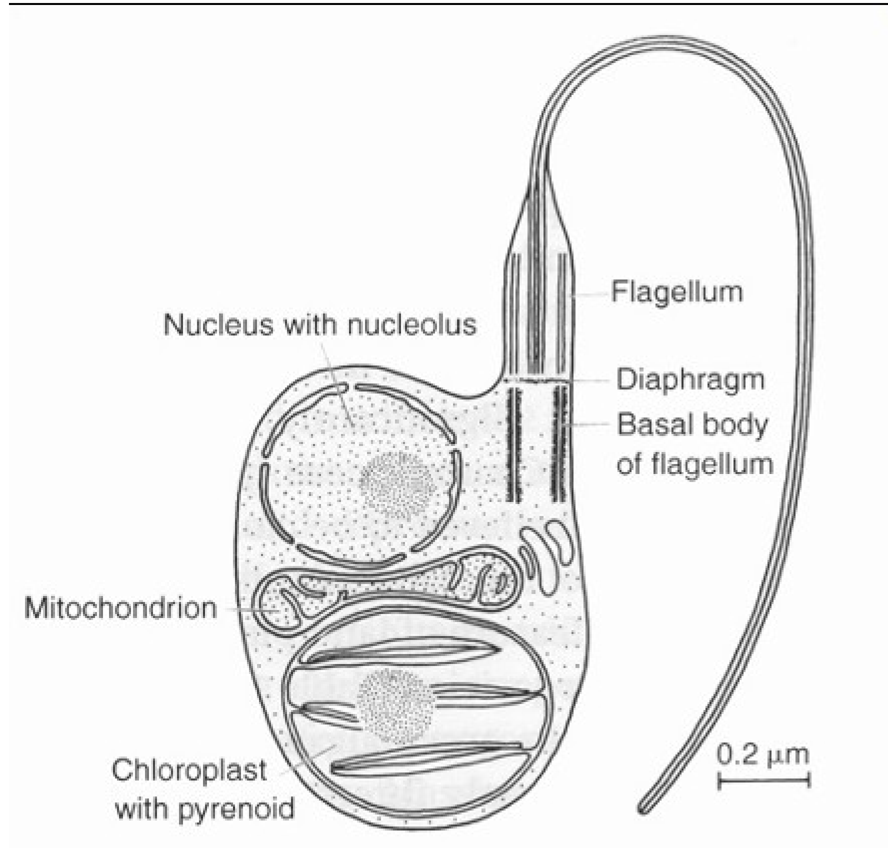
Acritarcha – very probably (partially) prasinophycean algae

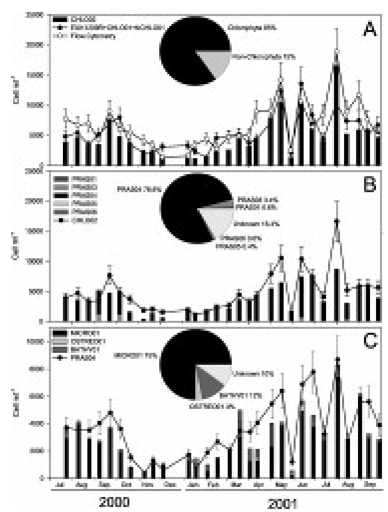


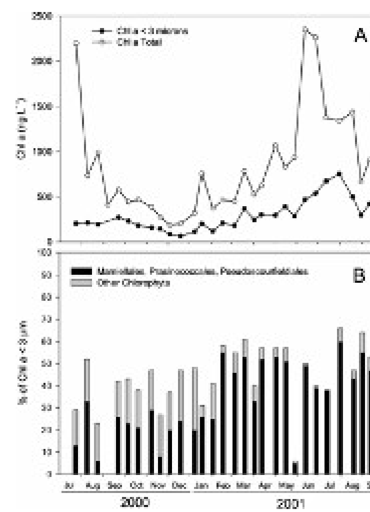
marine phytoplankton – cold seas

Mamiellophyceae
Micromonas









often as one of the dominants in picoplankton of cold shelf seas (i.e. North Sea)

Mamiellophyceae
Ostreococcus

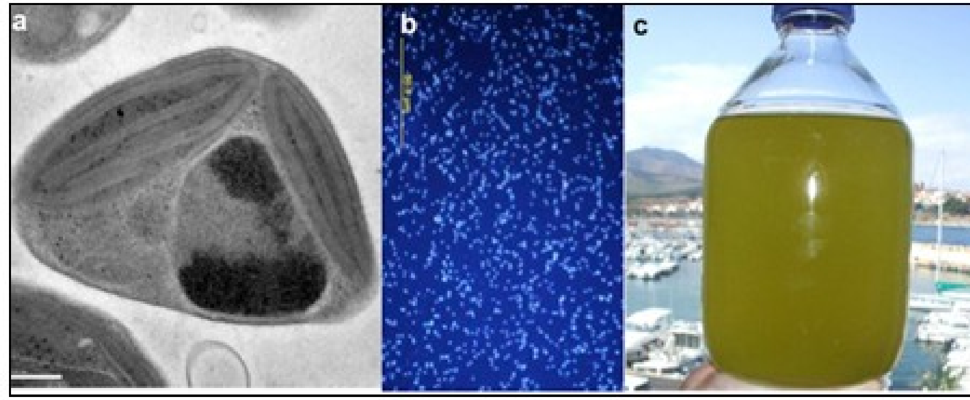
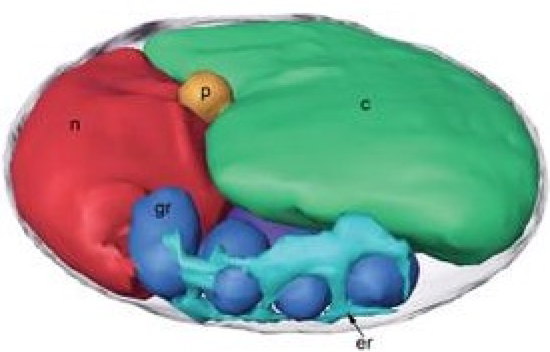


Photo: by Moreau lab, CNRS
a. TEM picture of Ostreococcus tauri
(ML Escande, Oceanological Observatory of Banyuls, France);
b. DAPI staining of O. tauri cells;
c. 2 Liter culture of O. tauri isolated from the bay of Banyuls seen in the background.

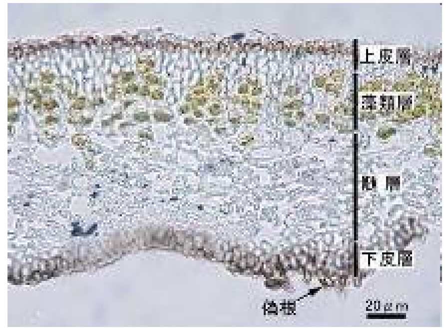


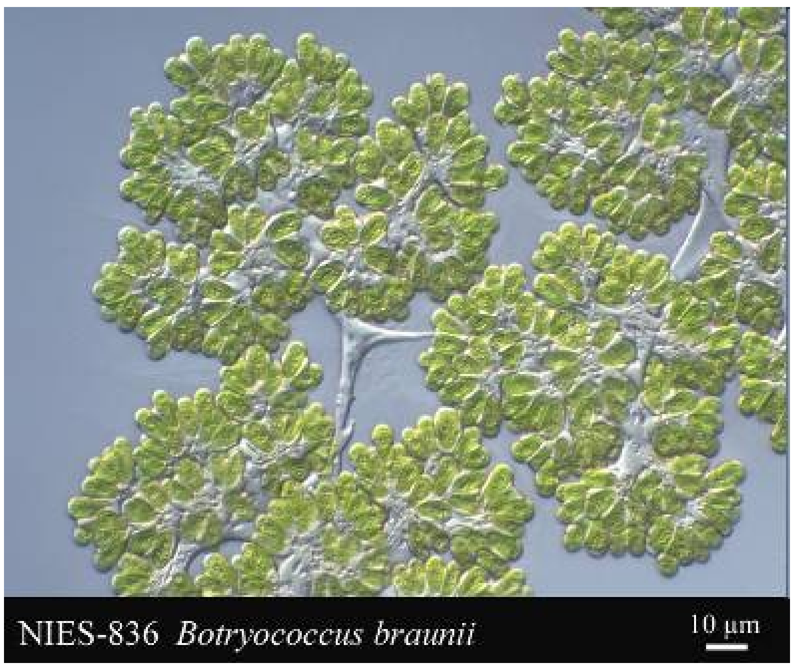
Electron cryotomographic reconstruction of an *O. tauri* cell. n = nucleus; c = chloroplast; p = peroxisome; er = endoplasmic reticulum. Source

- described in 1994 – plankton in Étang de Thau
- the smallest known free-living eukaryotic organism

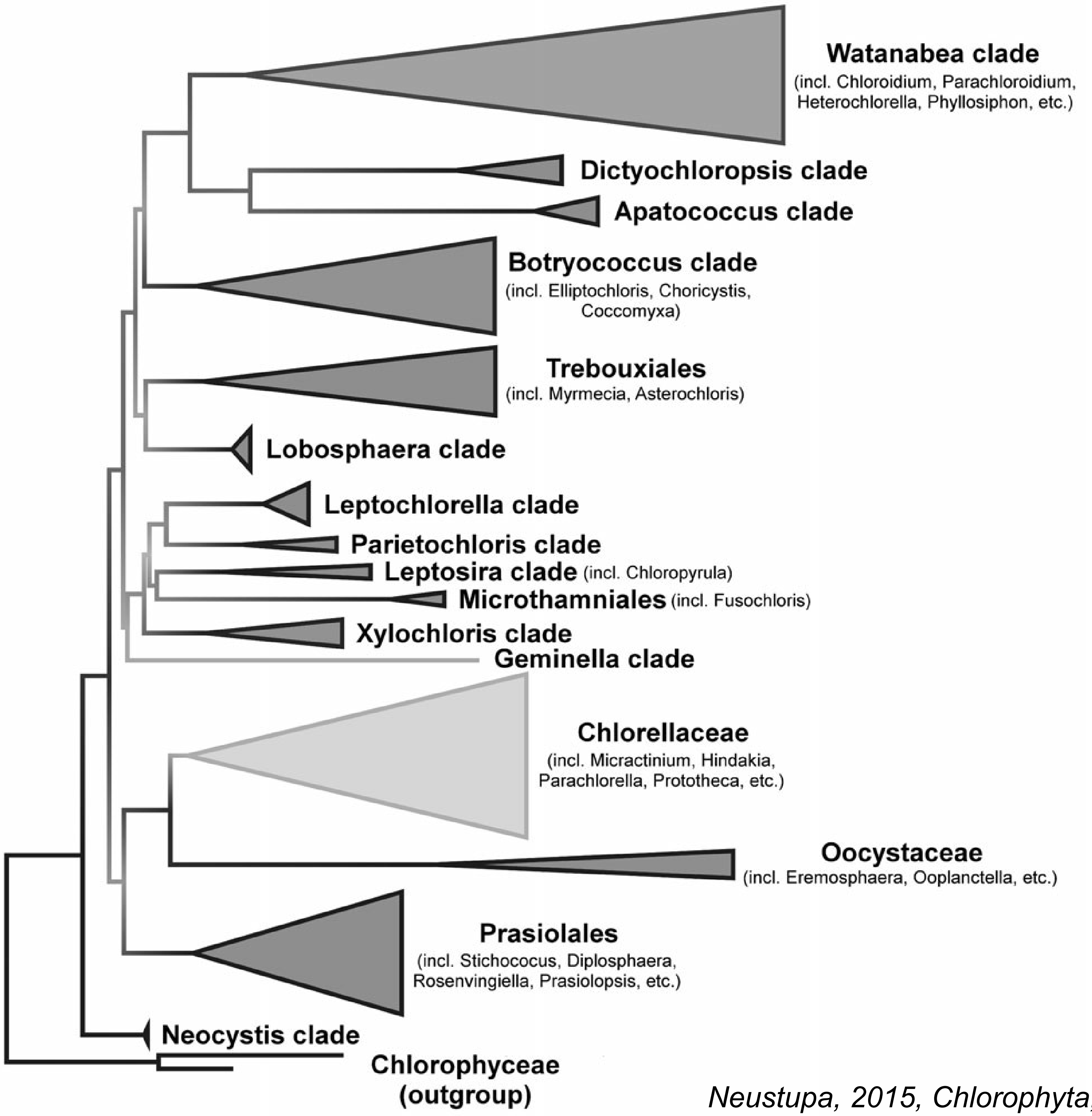
Třída: **Trebouxiophyceae**

Trebouxia – the most frequent fotobiont



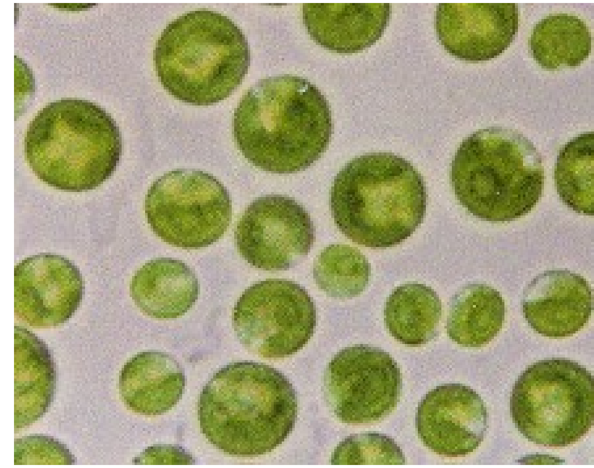


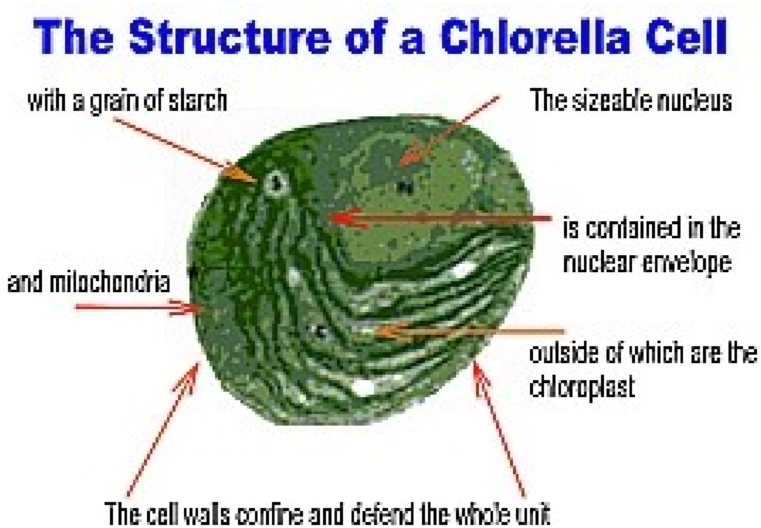
multiple successful transitions to terrestrial habitats but also several freshwater lineages

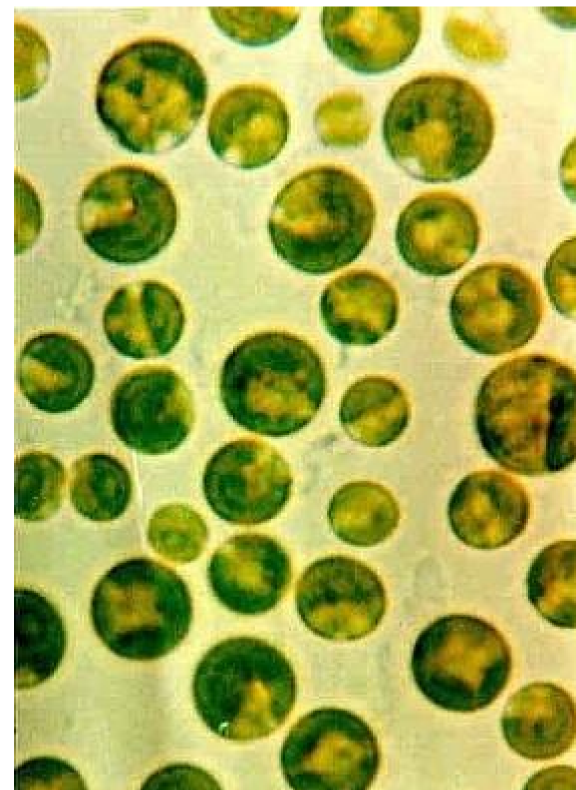


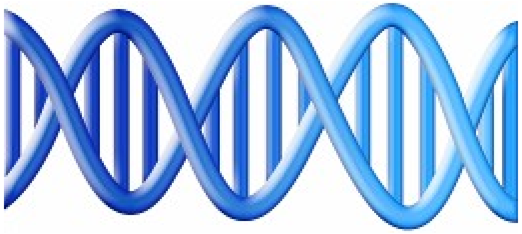
Neustupa, 2015, Chlorophyta, In: Syllabus of Plant Families

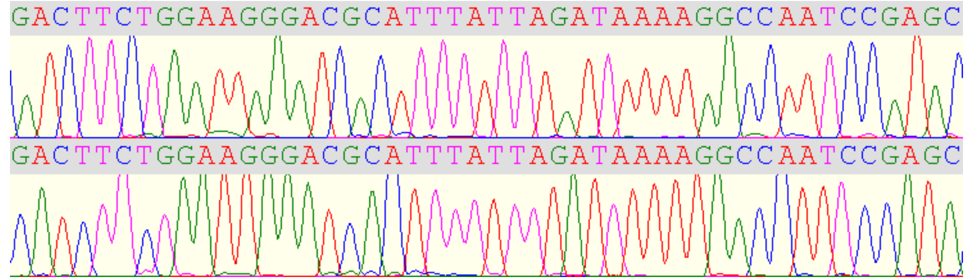
"Chlorella"



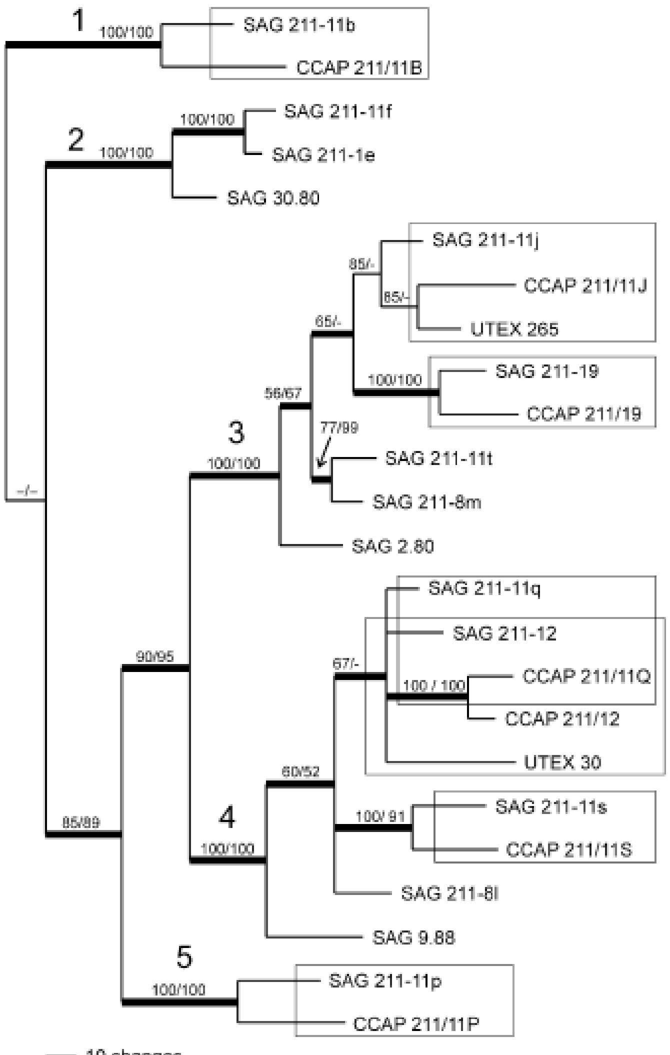

The Structure of a Chlorella Cell
with a grain of starch
The sizeable nucleus
is contained in the nuclear envelope
and mitochondria
outside of which are the chloroplast
The cell walls confine and defend the whole unit





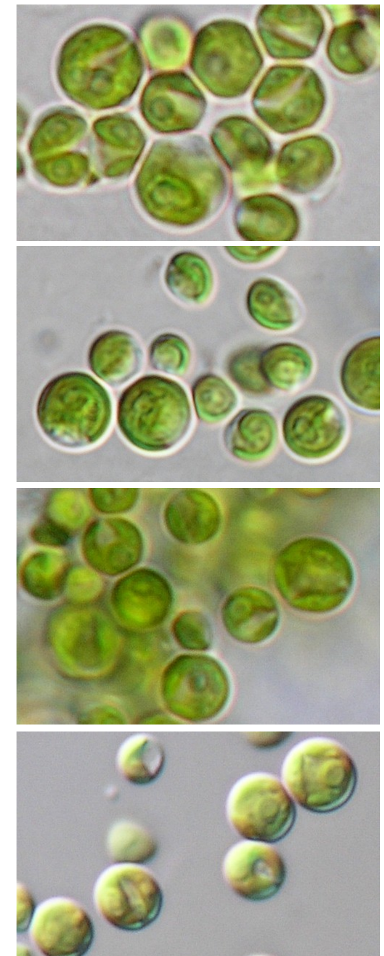


Chlorella vulgaris



AFLP, MP phylogenetic tree

cryptic diversity hampers
defining species by
traditional (morphological) methods

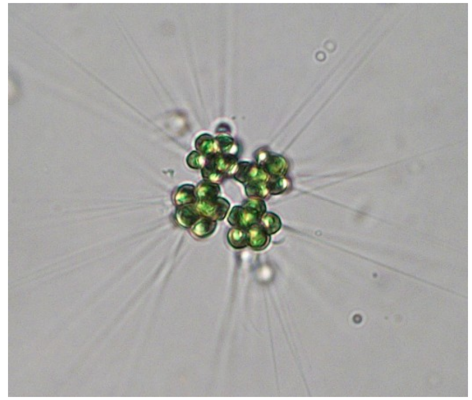


Müller et al., 2005, J. Phycol. 41:1236-1247.

chlorella business…

Chlorella vs. *Micractinium*

herbivore-driven phenotypic plasticity



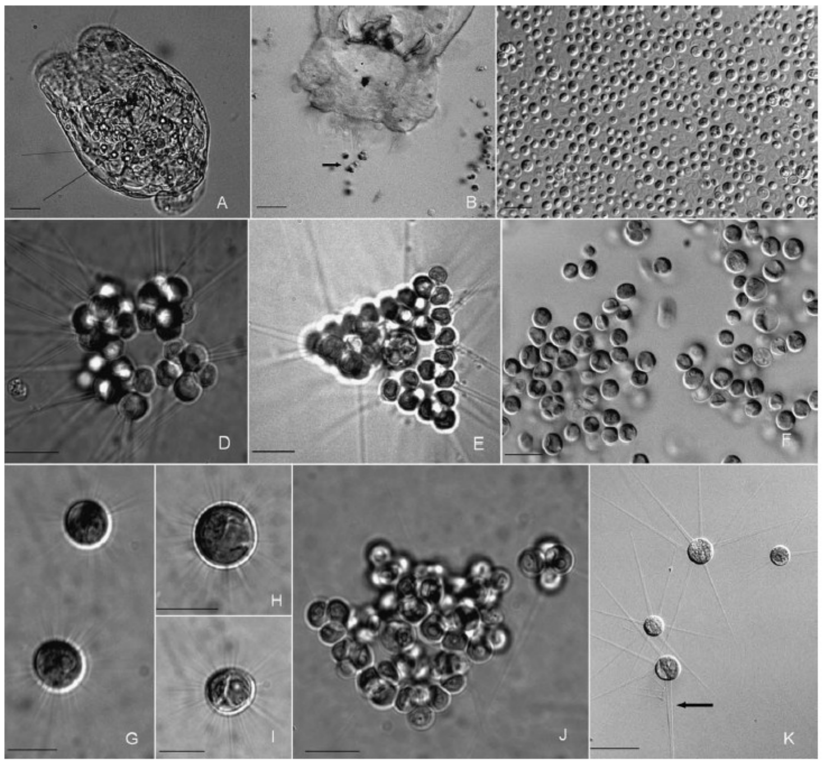
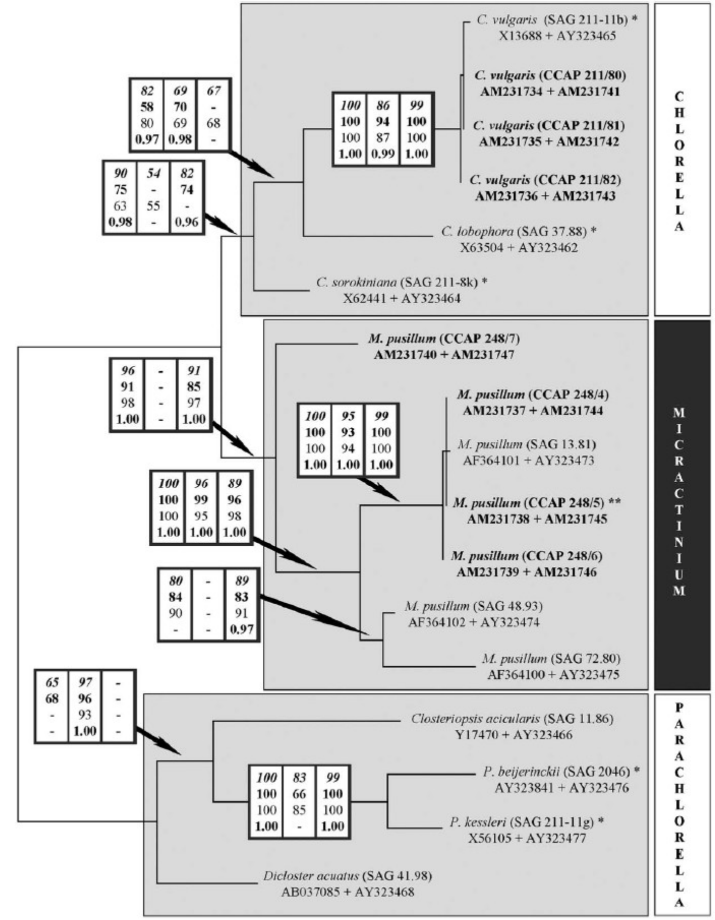


Figure 3. Organisms used in this study. Scale bars: **A, B.** 50 µm; **C:** 25 µm; **D–F, J, K.** 10 µm; **G–I.** 5 µm. **A.** *Brachionus calyciflorus* with ingested solitary, not-bristled cells of *Micractinium pusillum* (CCAP 248/5) (arrowhead). **B.** *Brachionus calyciflorus* ingesting coenobia of *Micractinium pusillum* (CCAP 248/5) (arrowhead). **C.** *Chlorella vulgaris* (CCAP 211/80). **D–K.** *Micractinium pusillum* under field and culture conditions. **D.** Cuboidal colony of eight spherical subcolonies; sampling site: Final Sewage Pond Nakuru, Kenya. **E.** Tetrahedral colony; sampling site: Speicher Radeburg, Germany. **F.** Strain CCAP 248/5, solitary cells without bristles in dense pre-cultures which can be used for the bristle induction experiments. **G–J.** Cultures from bristle induction experiments. **G.** Strain CCAP 248/7, tiny bristled solitary autospores. **H.** Strain SAG 13.81, bristled solitary vegetative cell. **I.** Strain CCAP 248/7, bristled mother cell with two autospores. **J.** Strain SAG 13.81, spherical colonies with or without bristles. **K.** Strain CCAP 248/5 after 24 h under grazing test conditions. The solitary cells developed strong bristles (arrow).



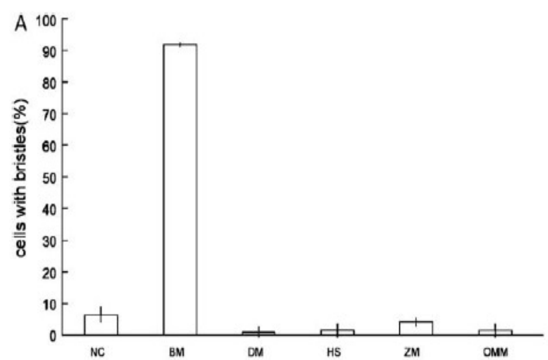
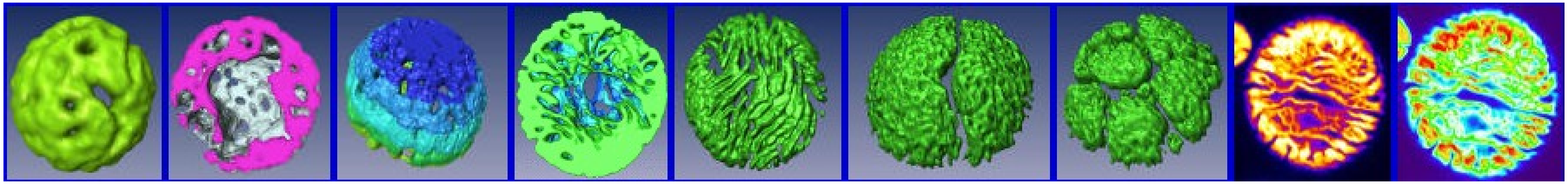
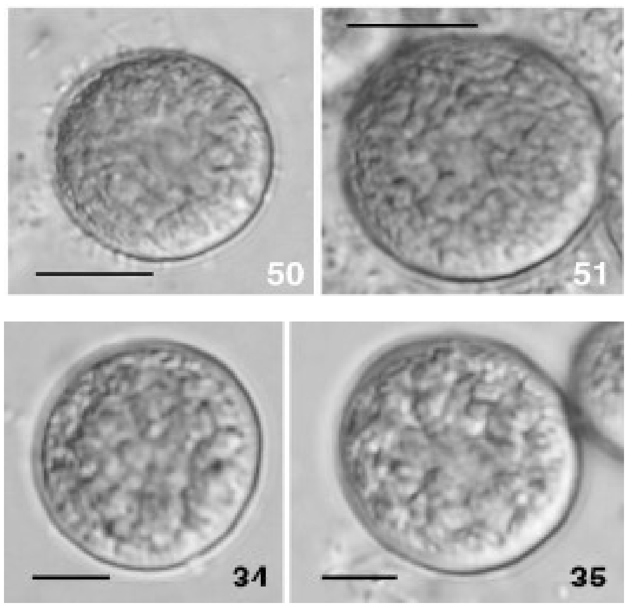


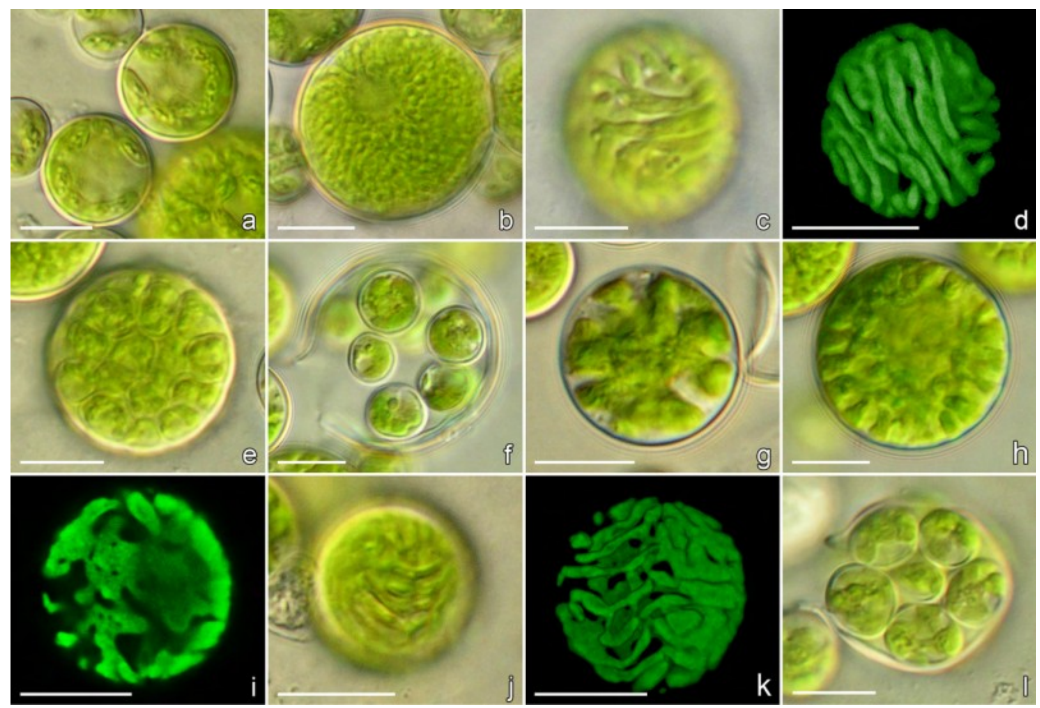
Figure 4. Influence of different test media on induction of bristle development in *Micractinium pusillum*. **A.** Percentage of bristled cells in strain CCAP 248/5 under the influence of different media, expressed as mean values (±1 SD, $n = 3$). *Abbreviations*: NC = Negative control; BM = *Brachionus* culture medium filtrate; DM = *Daphnia* culture medium filtrate HS = Humic substances; ZM = Z-medium; OMM = *Micractinium* culture medium from dense pre-culture. **B.** Percentage of bristled cells in

Luo et al., 2006, Protist 157: 315-333.

Genera *Symbiochloris* and *Dictyochloropsis* as examples of semicryptic evolutionary lineages



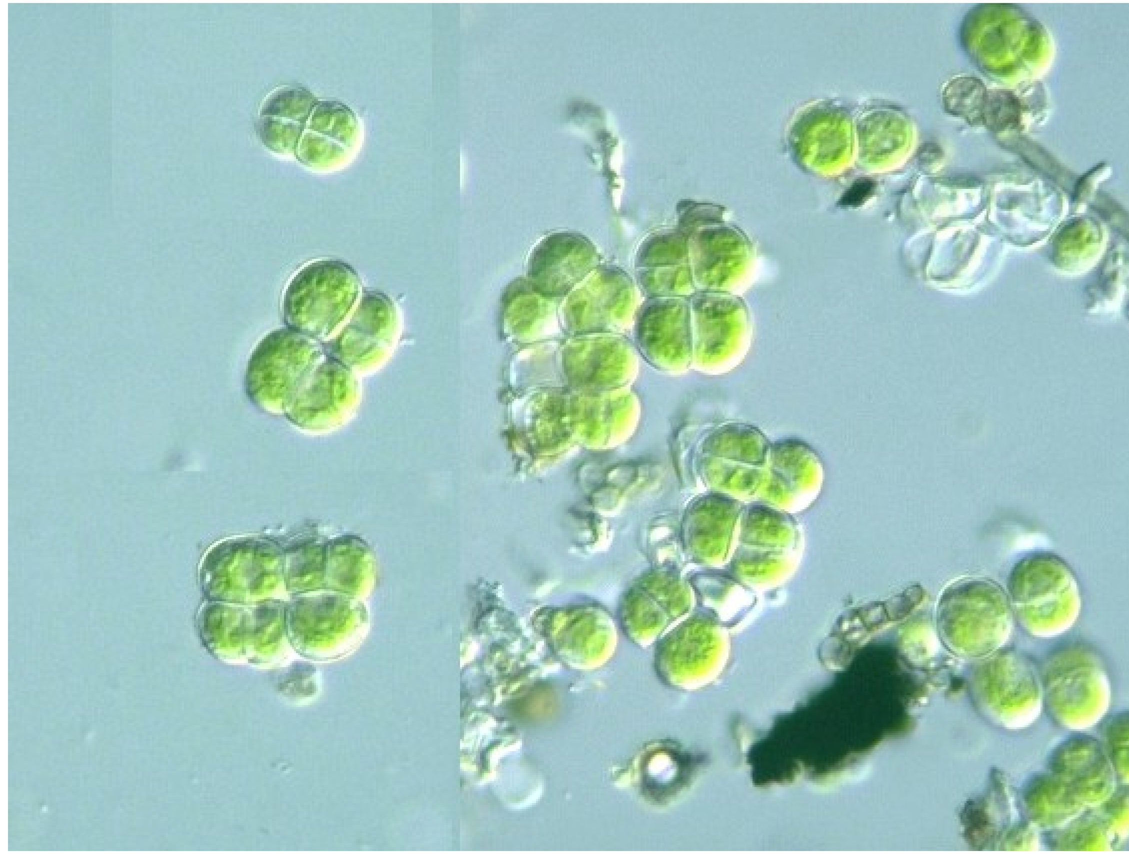




terestrial biotopes – biofilms on bark and stones

Škaloud et al., Phycologia, 2005, 44:261-269.

Apatococcus

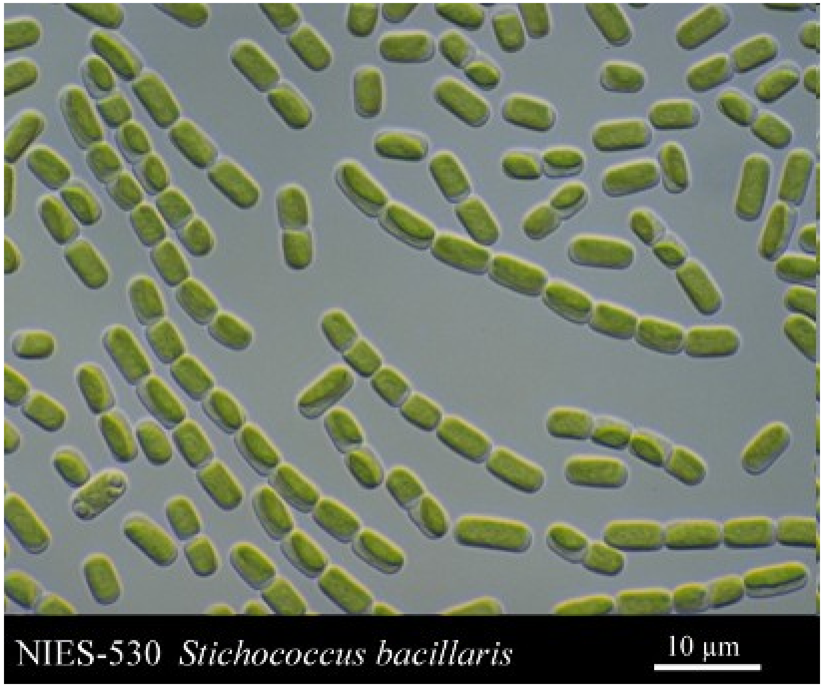


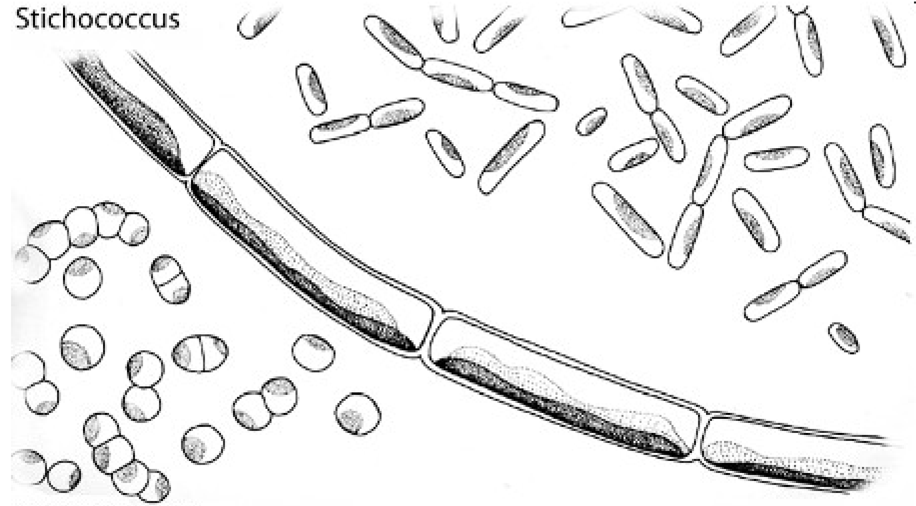
„the most frequent" alga in the world?

sarcinoid, colonial thallus made by coccoid cells

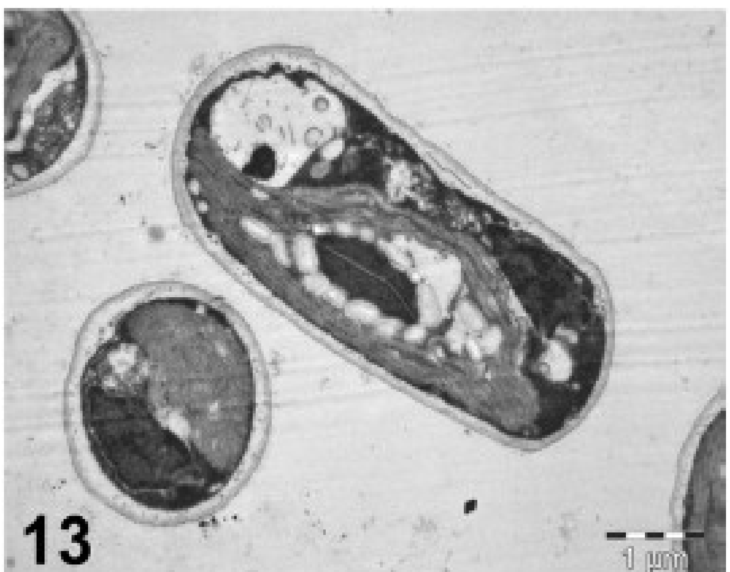
mixotrophic nutrition → capability of surviving in extremely shaded microhabitats

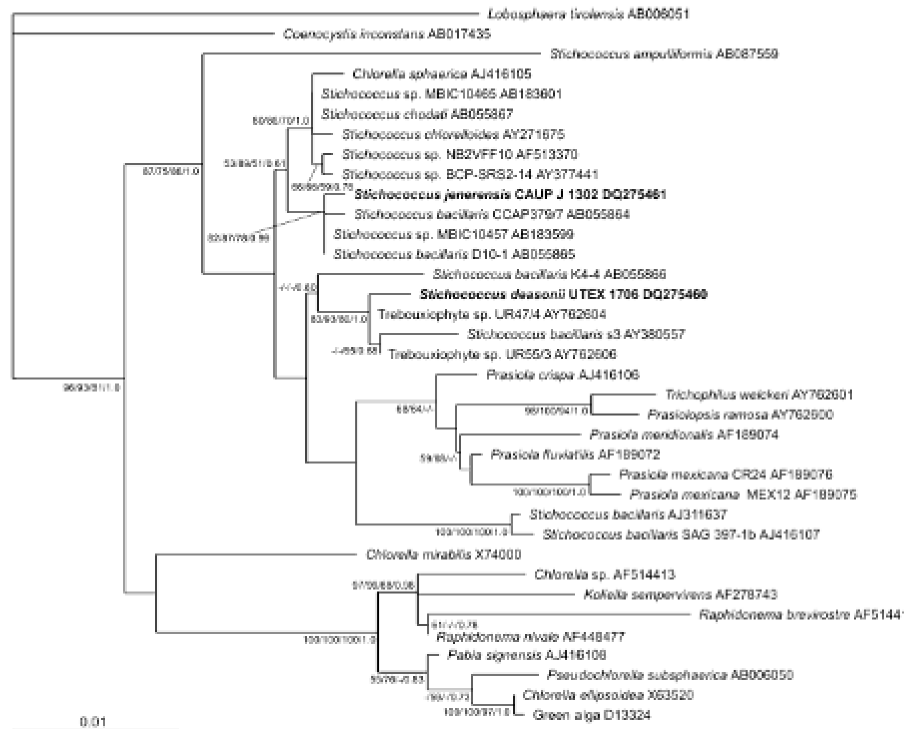
Stichococcus (Prasiolales)





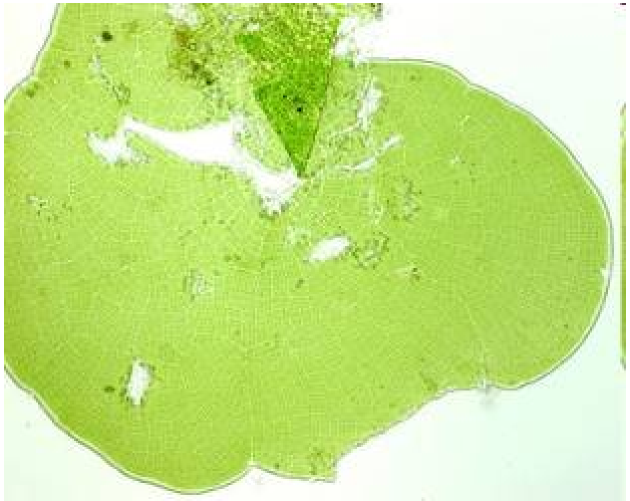
After Entwisle et al.(1997)





Prasiola (Prasiolales)

P. stipitata



P. crispa

aquatic and terrestrial multicellular and macroscopic thalli in Trebouxiophyceae

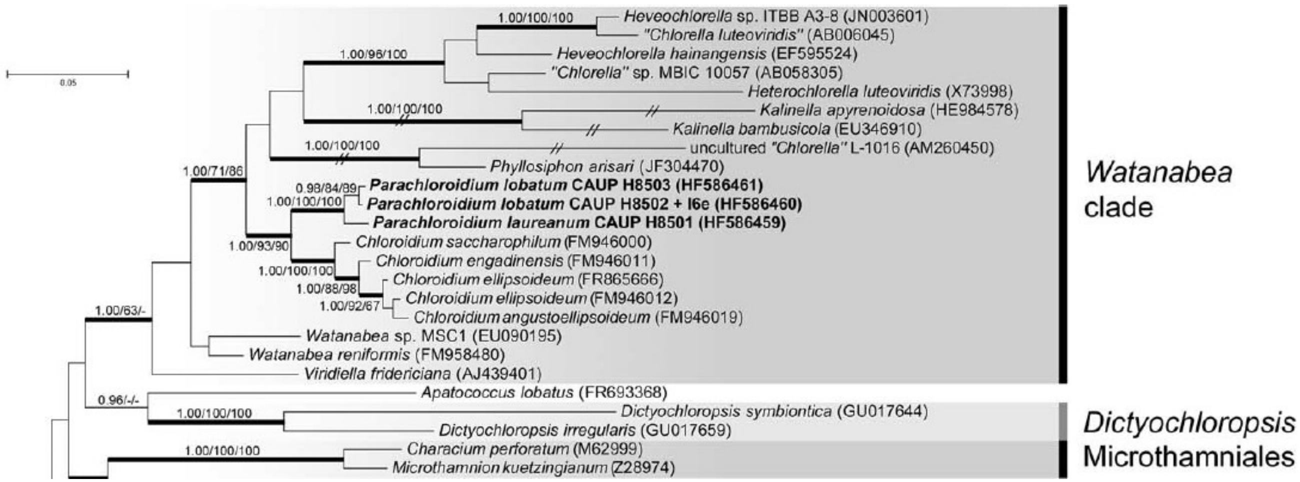
westarctica.wiki

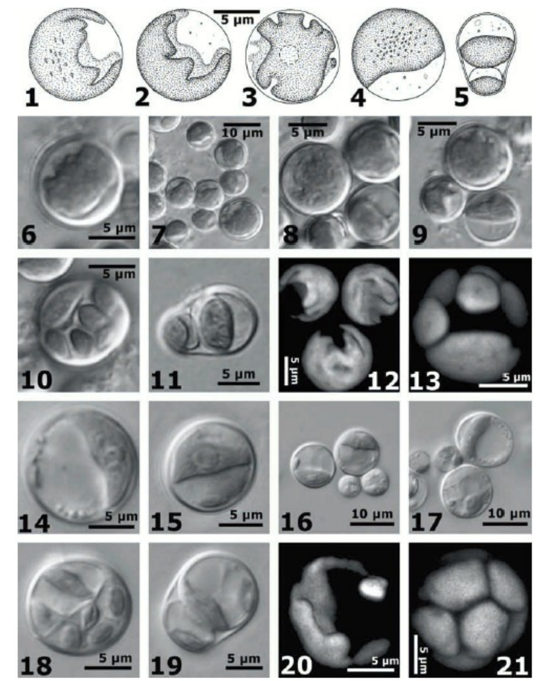
P. stipitata

algaebase.org

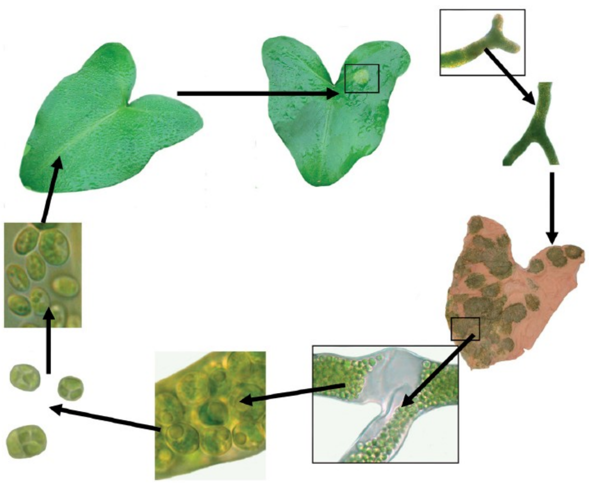
Watanabea clade

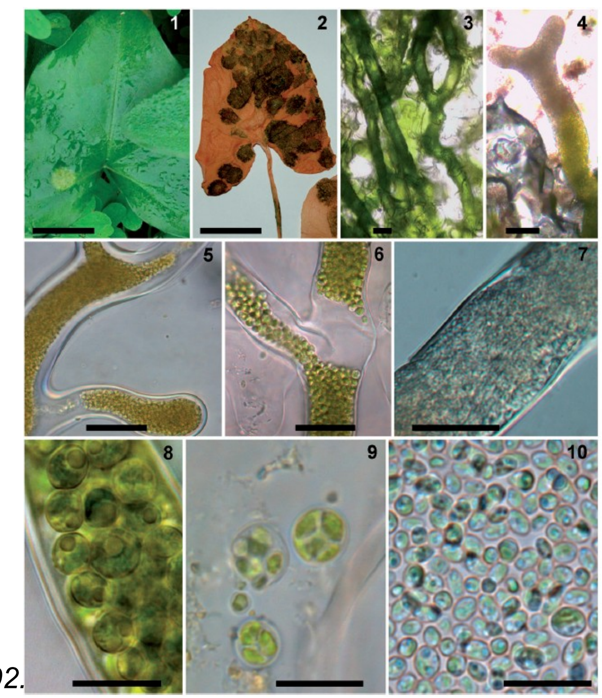
(genera *Kalinella, Chloroidium, Parachloroidium, Phyllosiphon*, etc.)



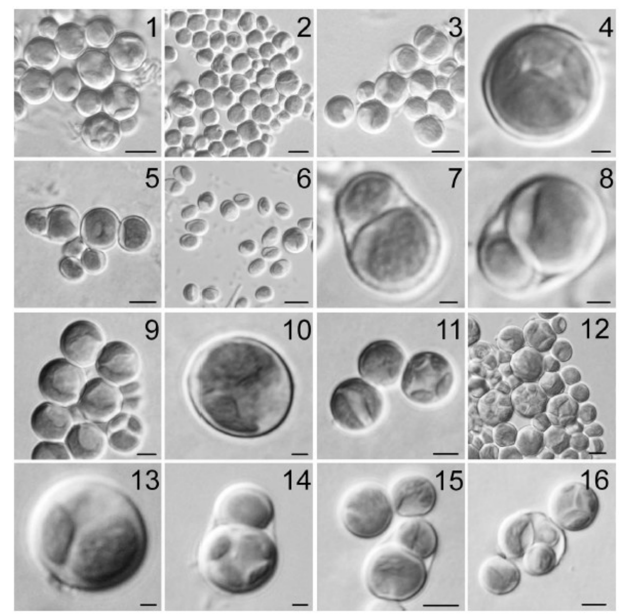


Kalinella





Phyllosiphon

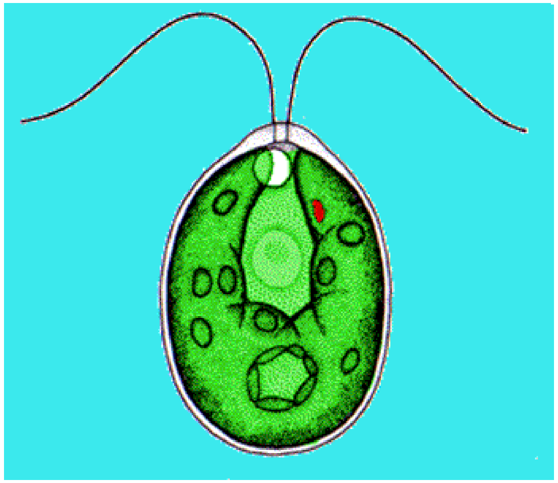


Parachloroidium

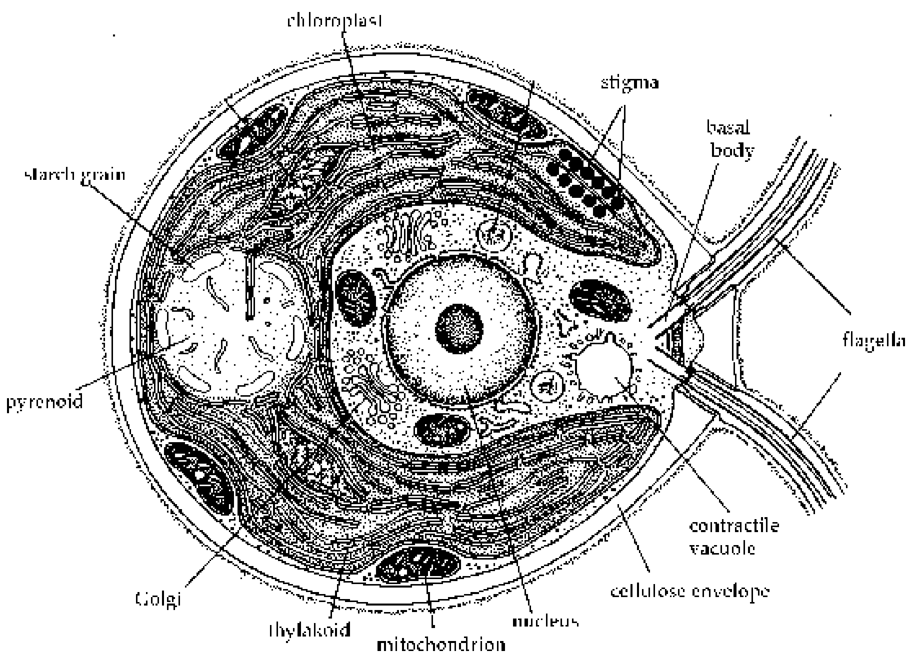
Neustupa et al. 2009, Phycol. Res. 57: 159-169.
Aboal & Werner 2011, Eur. J. Phycol. 46: 181-192.
Neustupa et al. 2013, Phycologia 52: 411-421.

Třída: ***Chlorophyceae***

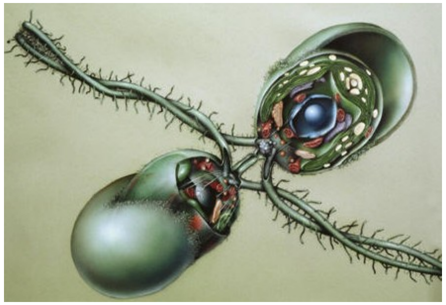
here belong most free-living „plant“ flagellates
coenobial or filamentous multicellularity
biotechnological importance – astaxanthin, beta-catoren production



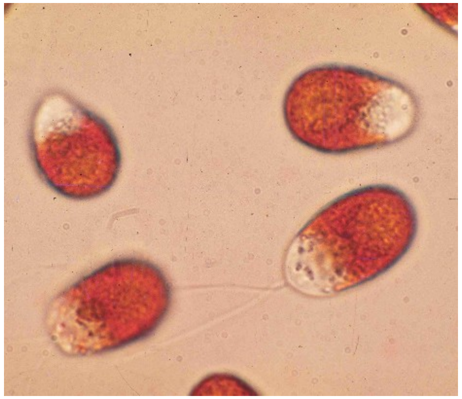
Chlamydomonas - model flagellated organism in Viridiplantae
(*Volvox* - plant coenobial multicellularity based on flagellated cells)



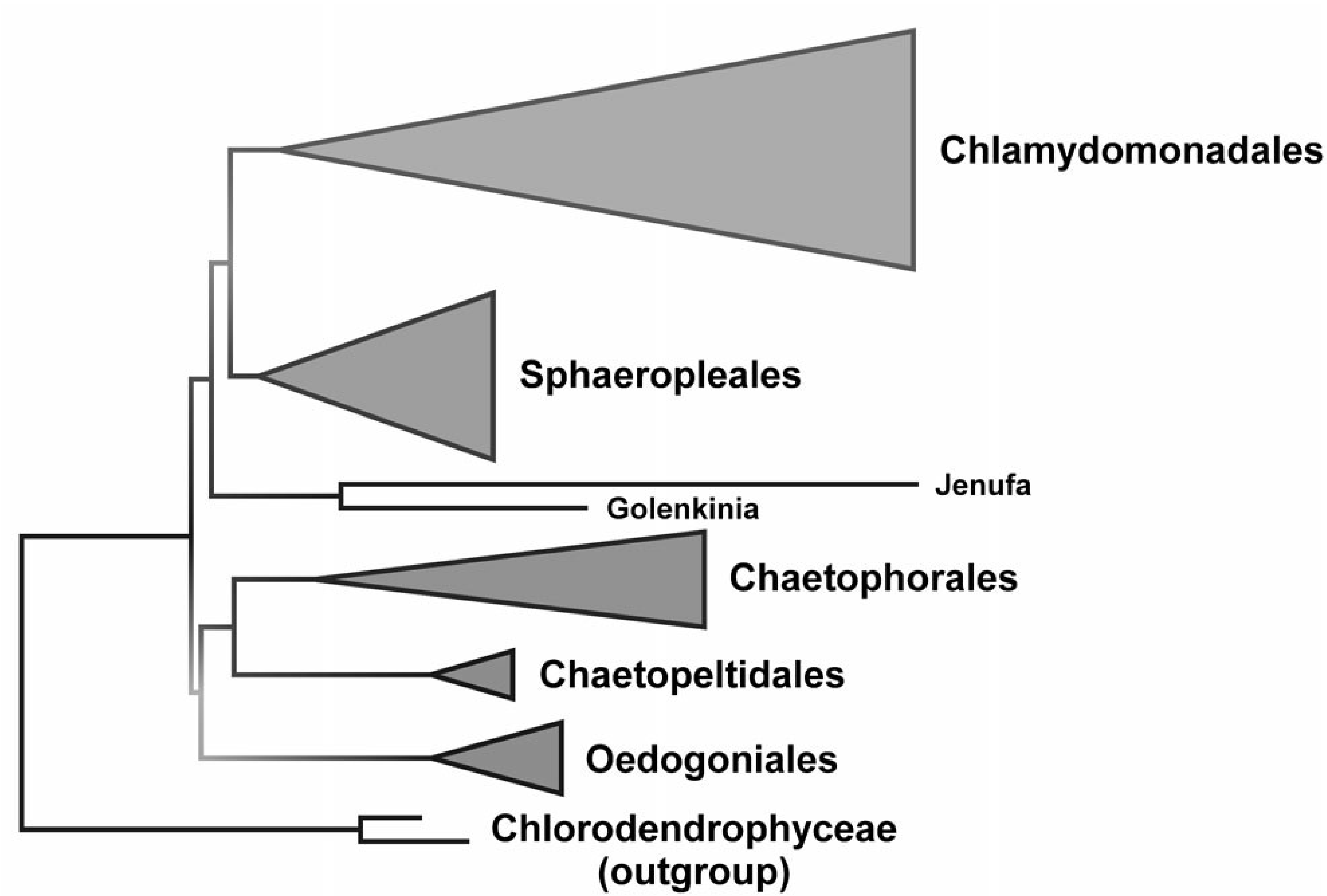
Chlamydomonas



Chlamydomonas - izogamie
(http://bioweb.uwlax.edu/bio203/s2007/awowale_john/reproduction.htm)

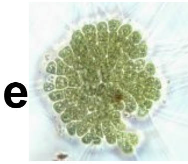


Dunaliella, Carteria



Neustupa, 2014, Chlorophyta, In: Syllabus of Plant Families

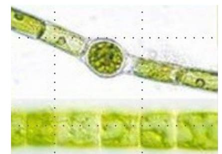
class: **Chlorophyceae**

order: **Chaetopeltidale** 

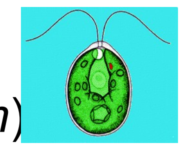
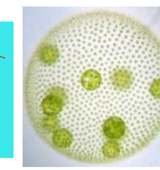
order: **Chaetophorales**
(*Chaetophora, Stigeoclonium, Dicranochaete*)

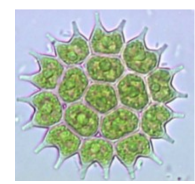
order: **Oedogoniales**
(*Oedogonium, Bulbochaete, Oedocladium*)

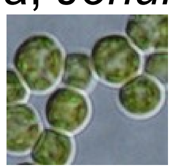
order: **Chlamydomonadales**
(*Carteria, Chlamydomonas, Dunaliella, Haematococcus, Volvox, Gonium*)

orer: **Sphaeropleales**
(*Scenedesmus, Desmodesmus, Pediastrum, Hydrodictyon*)

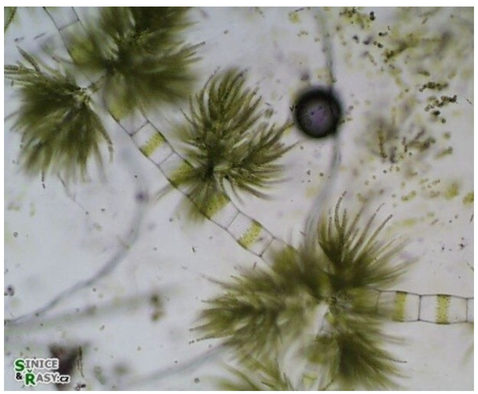
incertae sedis: *Golenkinia*, *Jenufa*

order: Chaetophorales

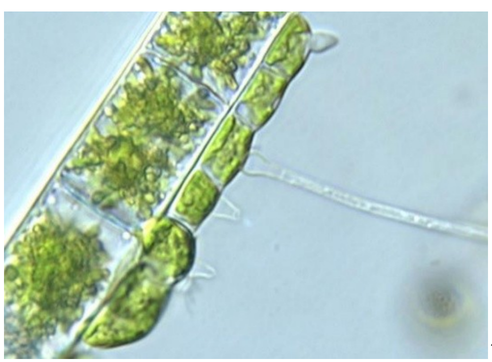



Stigeoclonium *Chaetophora*

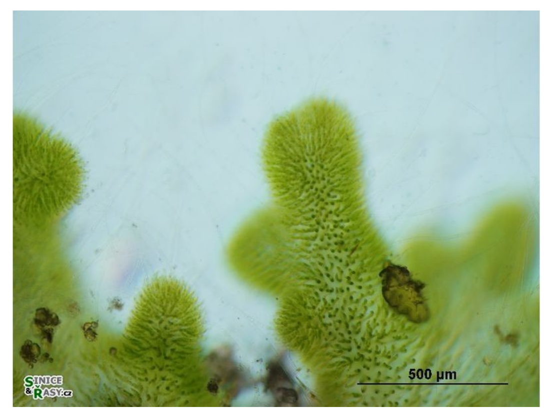


Draparnaldia


predominantly a freshwater lineage

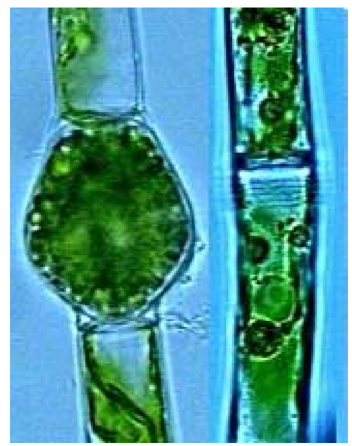


Aphanochaete

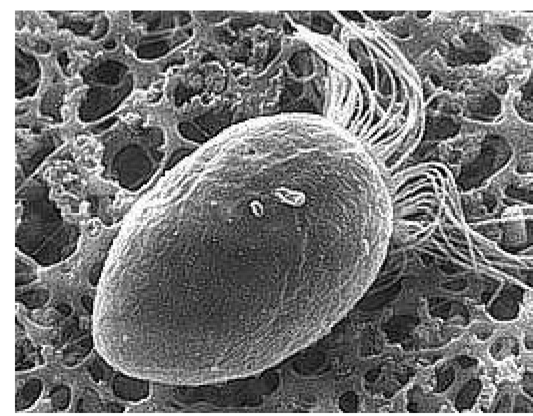



order: Oedogoniales

Bulbochaete



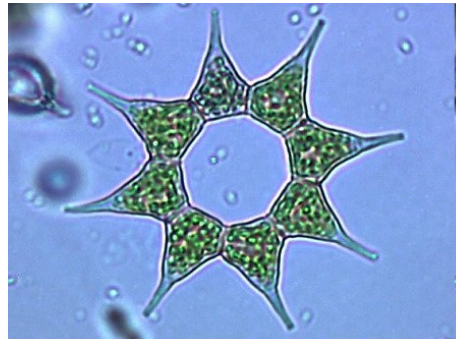
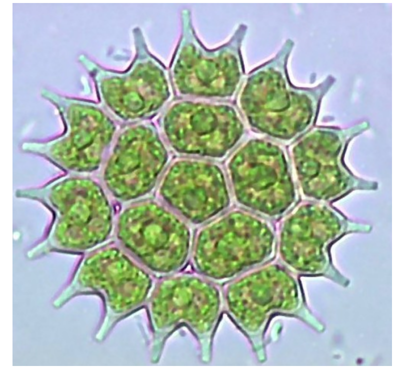
Oedogonium



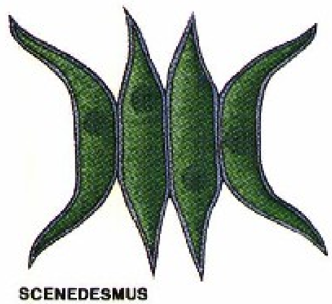
order: # Sphaeropleales

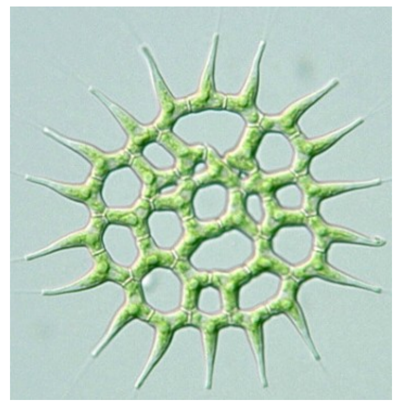
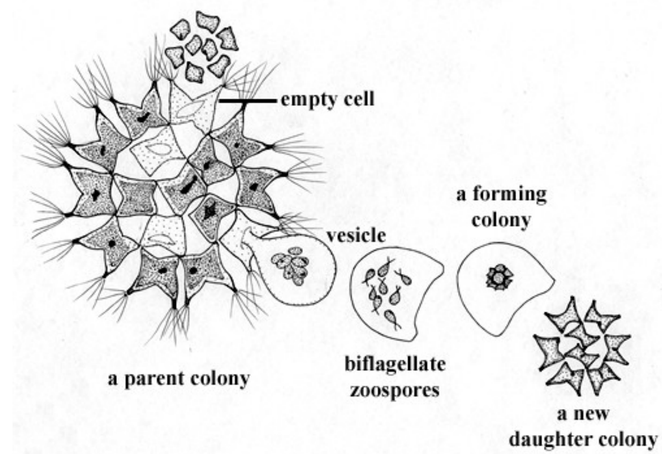
Pediastrum and relatives

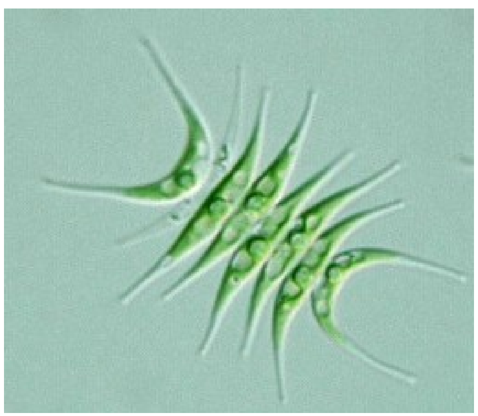
Scenedesmus and relatives
[incl. Desmodesmus, Acutodesmus, Pectinodesmus, Verrucodesmus, Chodatodesmus, etc...]
coccoid coenobial multicellularity

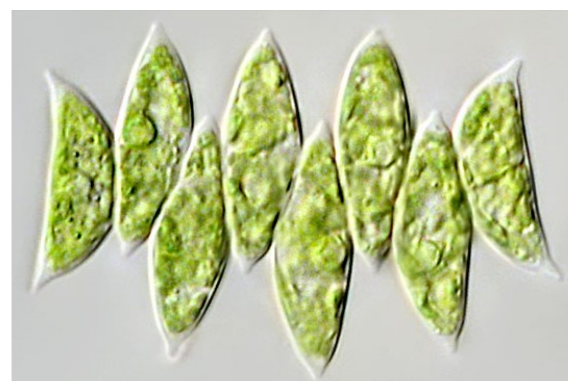
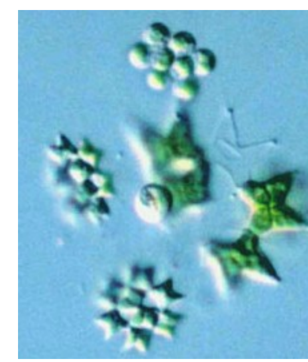

Pediastrum



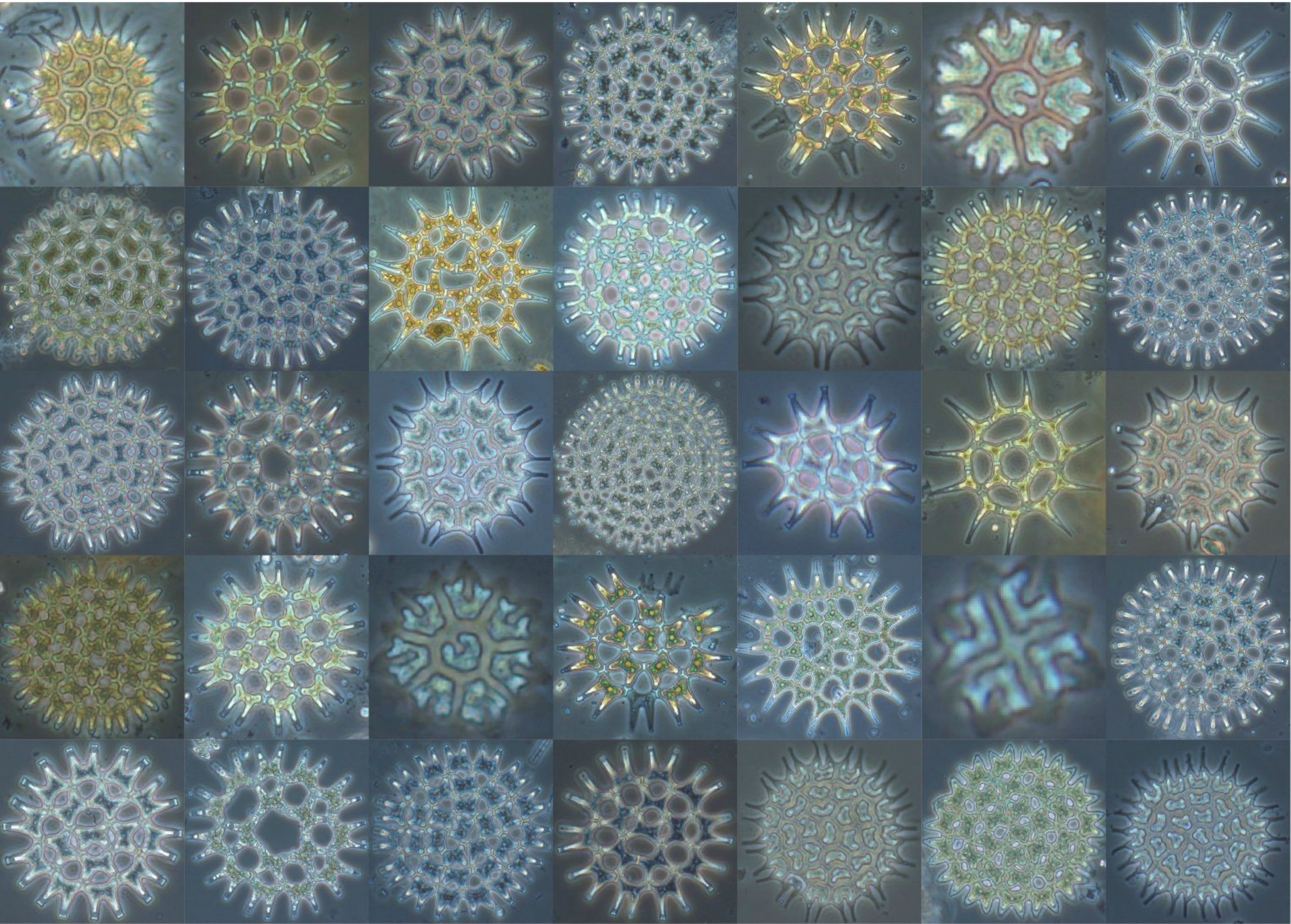


Scenedesmus, Desmodesmus

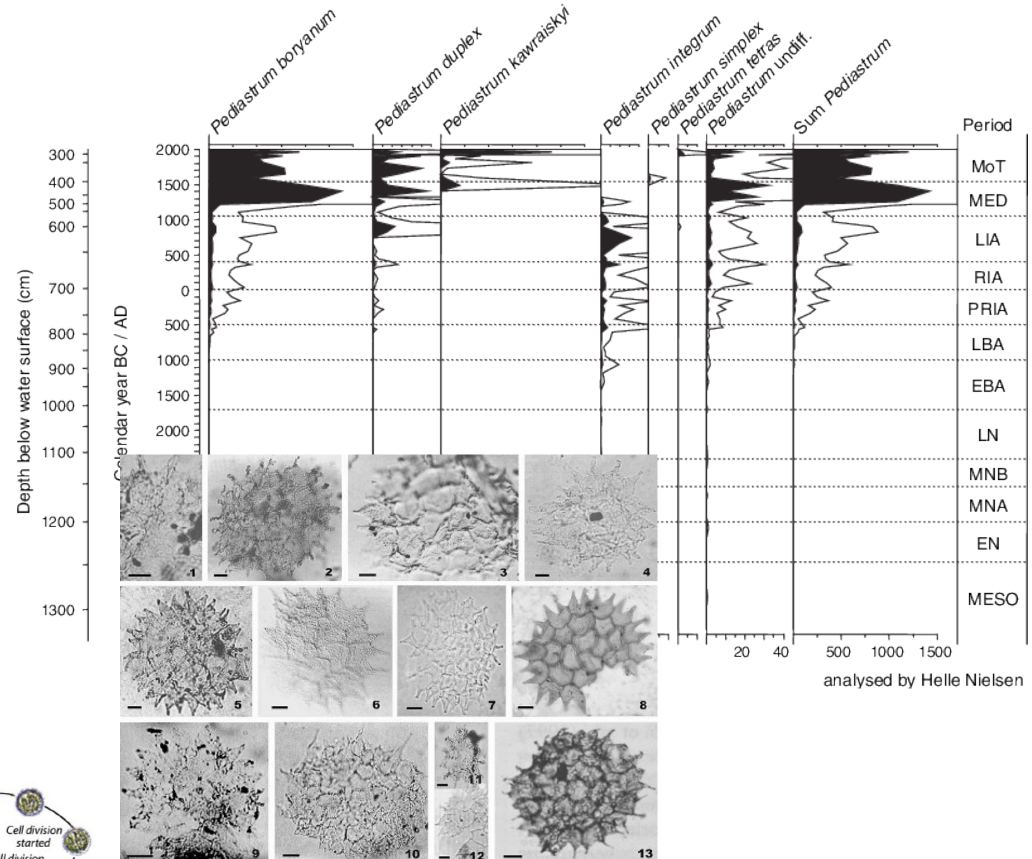
morphological plasticity (reaction norm of genotypes) – adaptation to herbivory and sinking stress

Pediastrum, Parapediastrum, Pseudopediastrum, Sorastrum, Monactinus, Lacunastrum, Stauridium, etc...



Bradshaw et al, 2005, The Holocene

subrecent eutrofication of a temperate lake



Zamaloa & Tell, 2005, Hydrobiologia

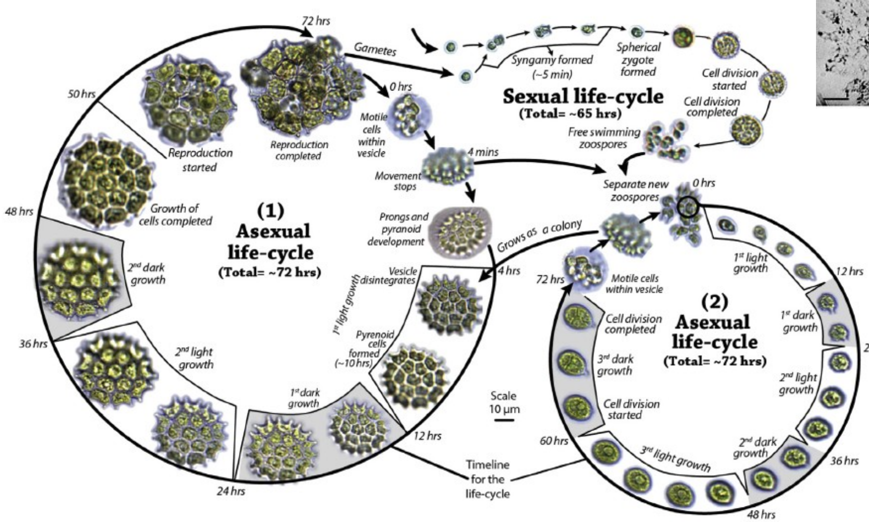
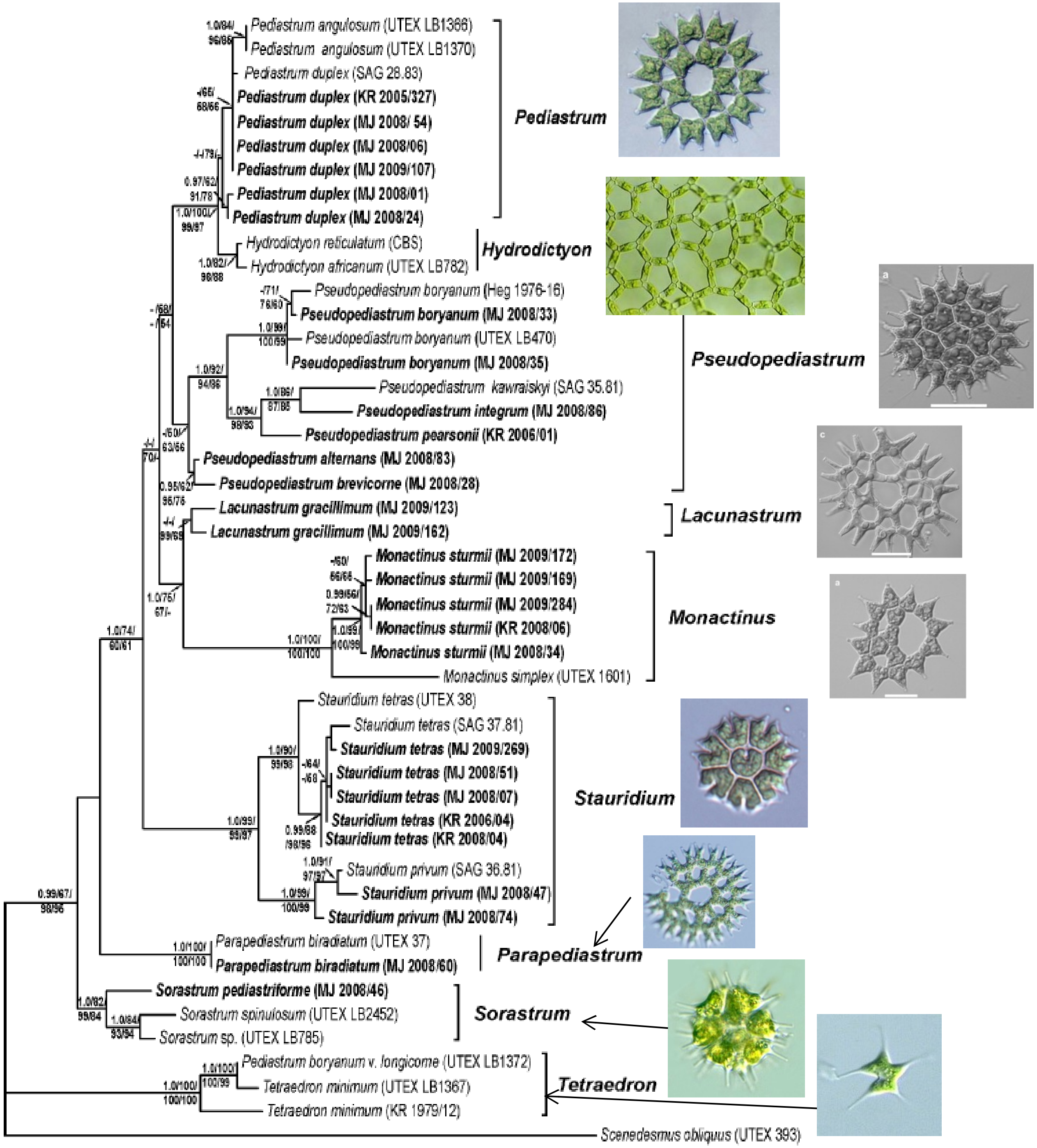


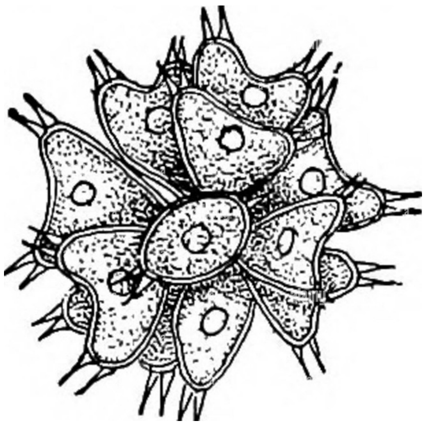
Fig. 3 – The asexual and sexual life-cycles of ***Pediastrum boryanum*** determined by observation of the growth of single cells/colonies grown in a microcosm under 250 µMol/m²/s (12:12 h light and dark cycle) at 20 °C.

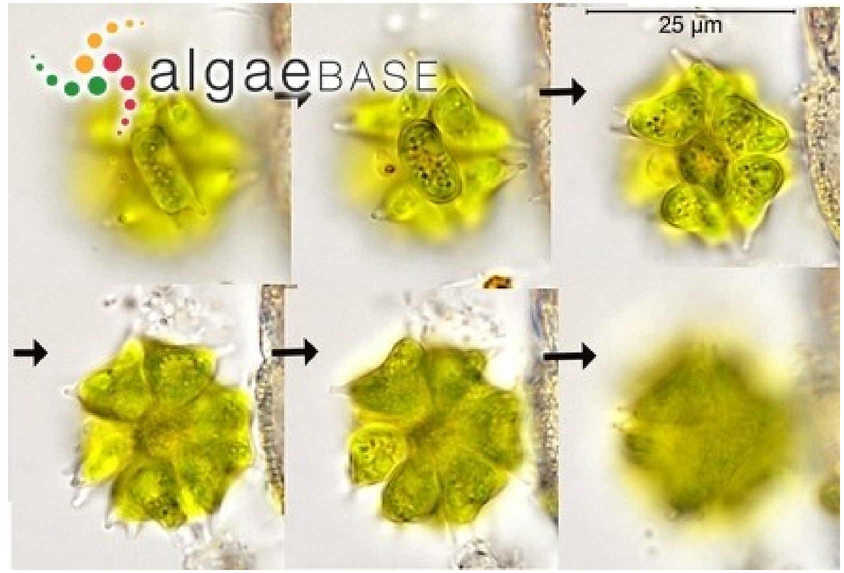
Park et al, 2014, Water Research 60

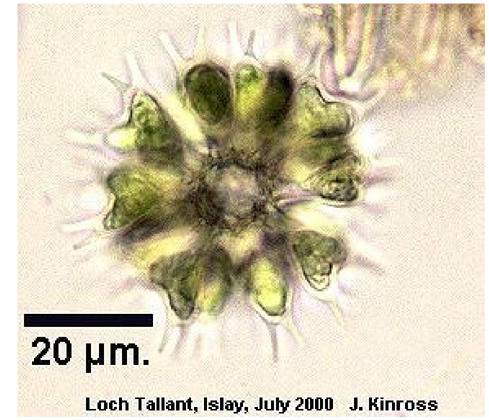


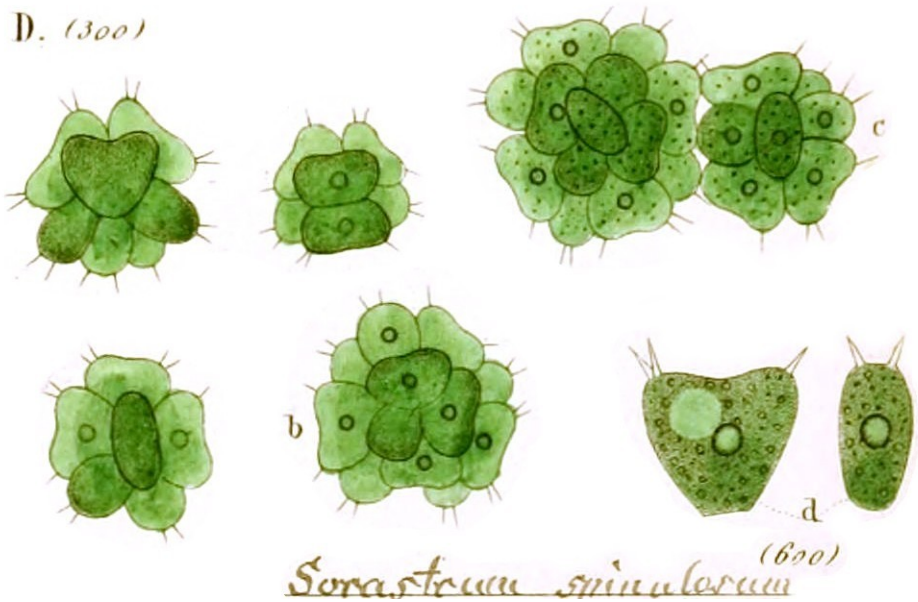
Jena et al, 2014, Fottea 14

Sorastrum



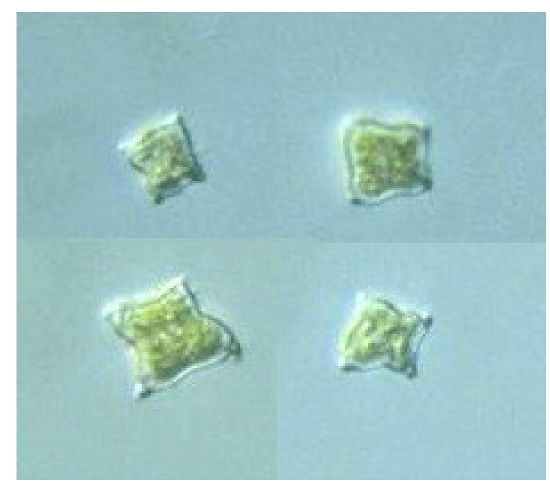






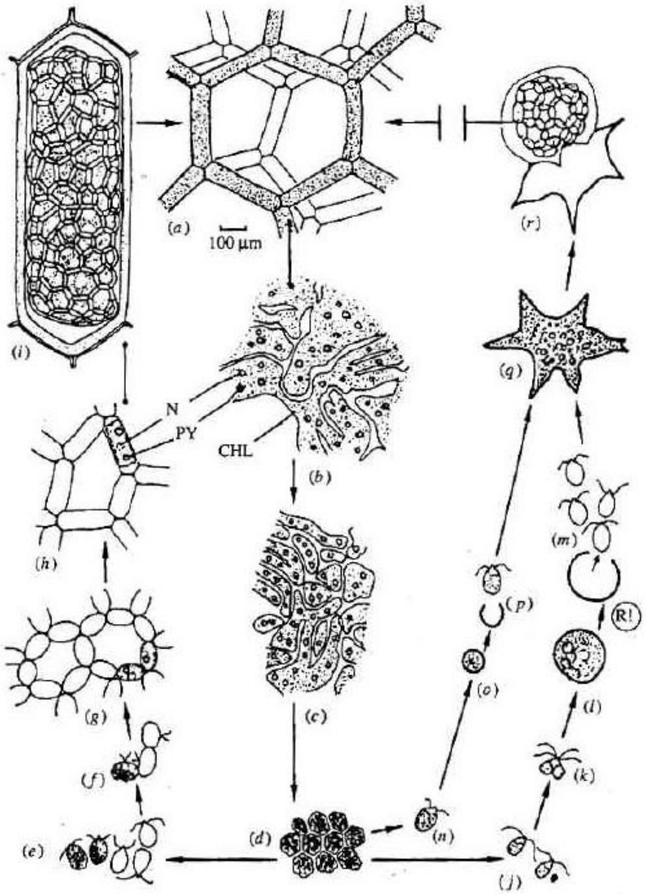
mostly (sub-)tropical eutrophic phytoplankton

Tetraedron

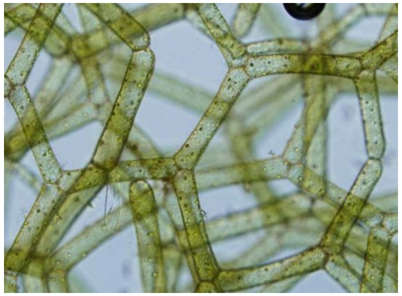


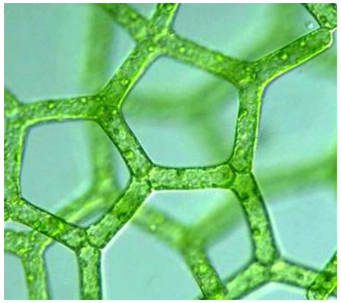
unicellular lineage,
sister to coenobial taxa

Hydrodictyon



haplontic life cycle, meiospores from a zygote, develop into the single-celled stage which produces coenobial plant



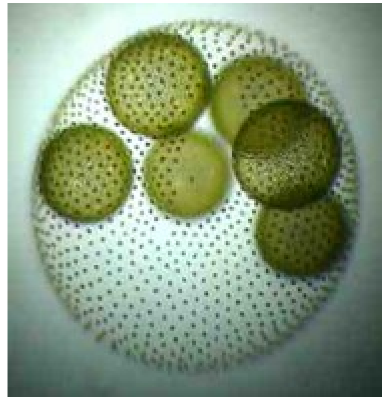


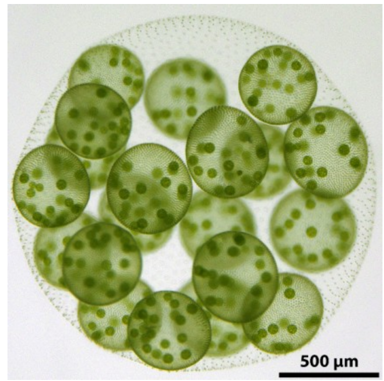
[Domin pond, Č.B.]

Chlamydomonadales

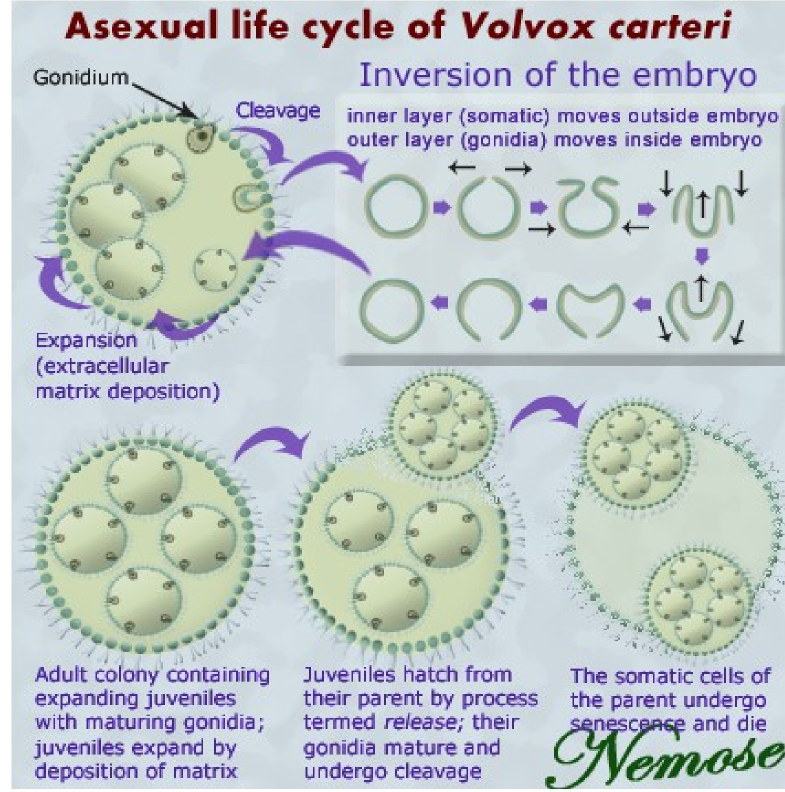
coenobial multicellularity of flagellates
(*Volvox*, *Gonium*, *Eudorina*)

Pleodorina

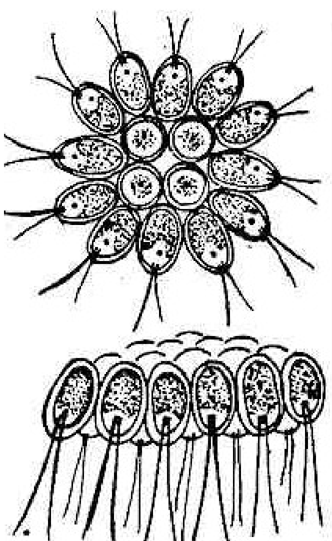




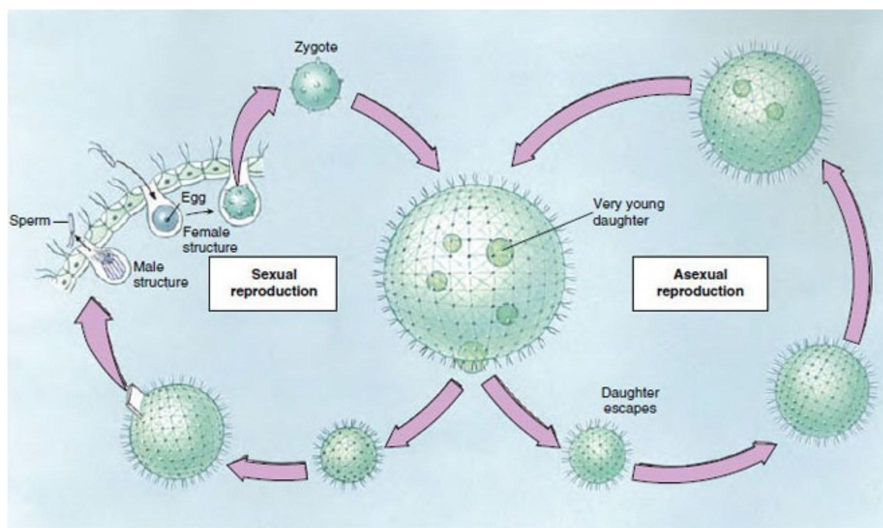
Volvox

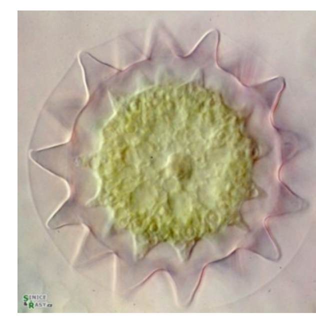


http://www.metamicrobe.com/volvox/



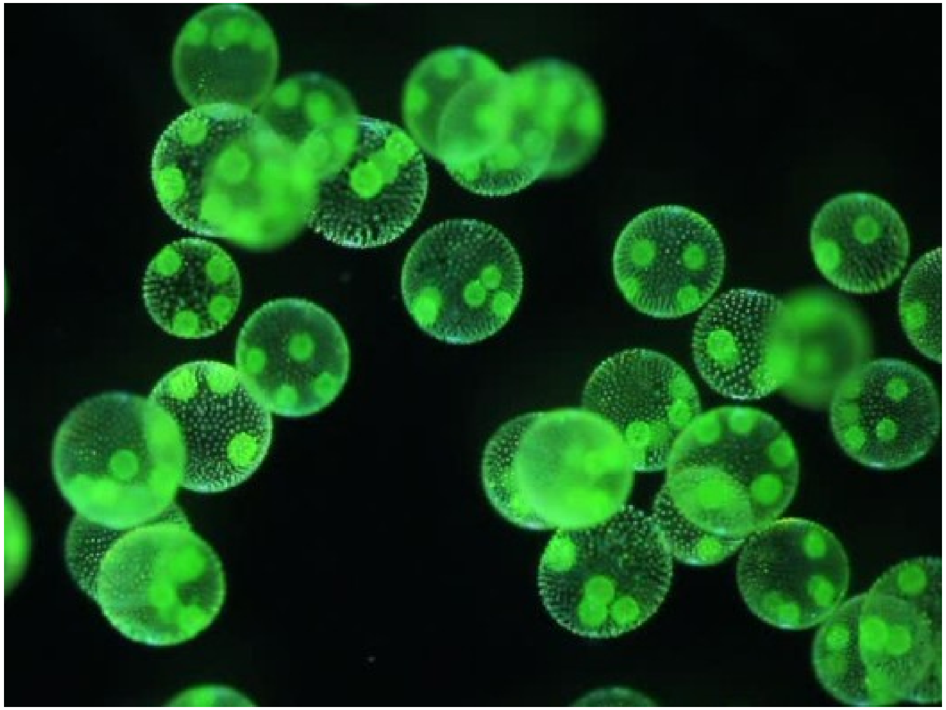
Gonium

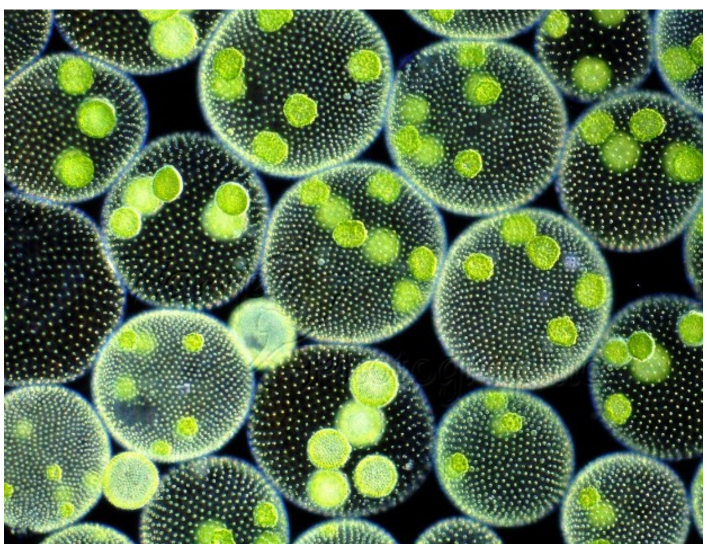


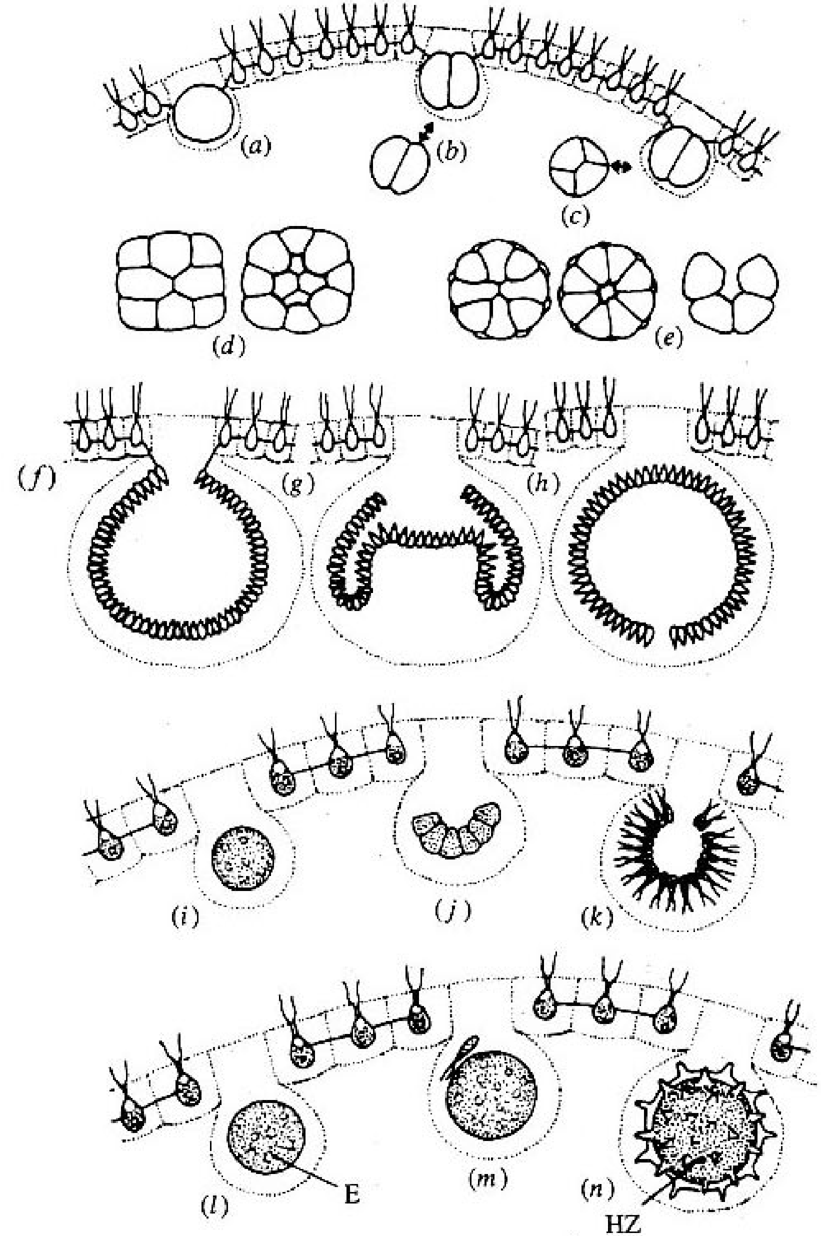


Volvox - zygospore

Volvox

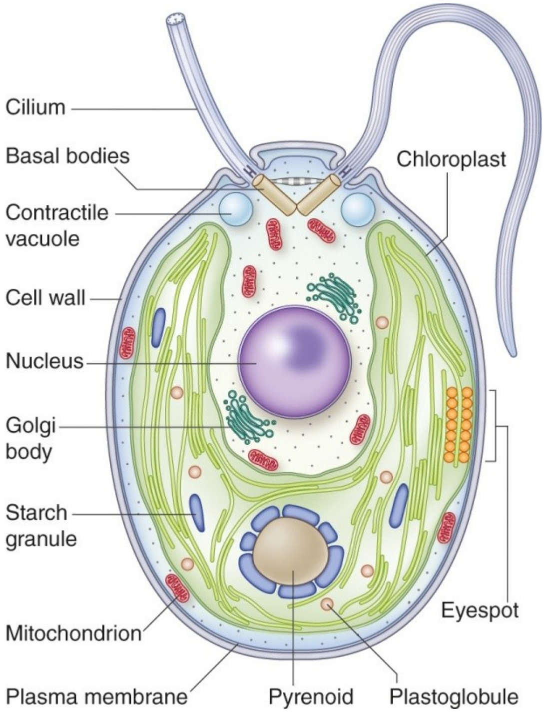


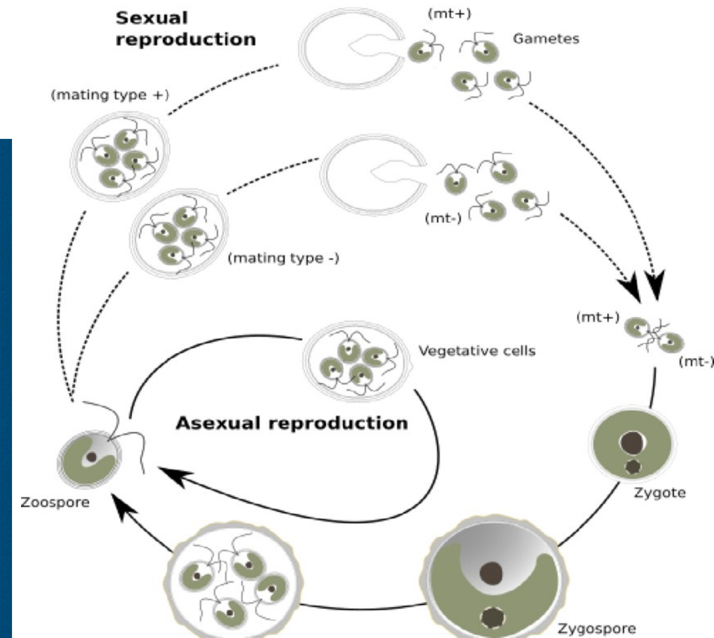




asexual: daughter colonies, sexual: oogamy

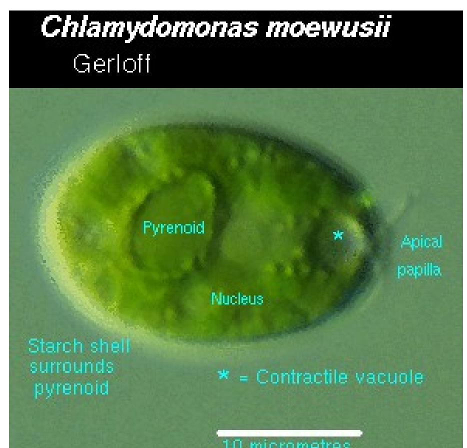
Chlamydomonas





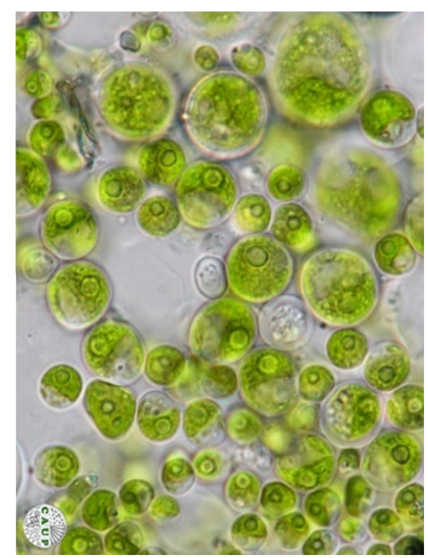
Baudelet et al., 2017, Algal Res.

the model free-living flagellated plant organism (*C. reinhardtii*)

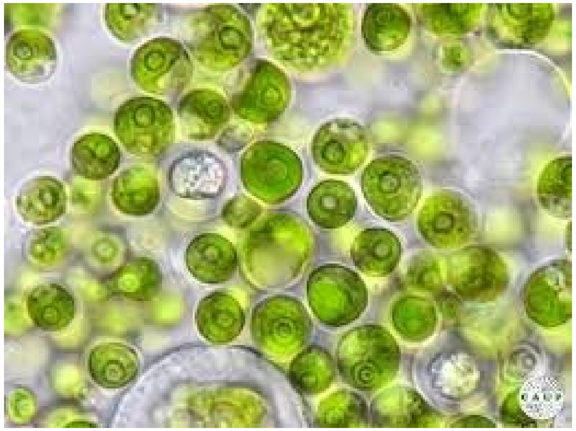


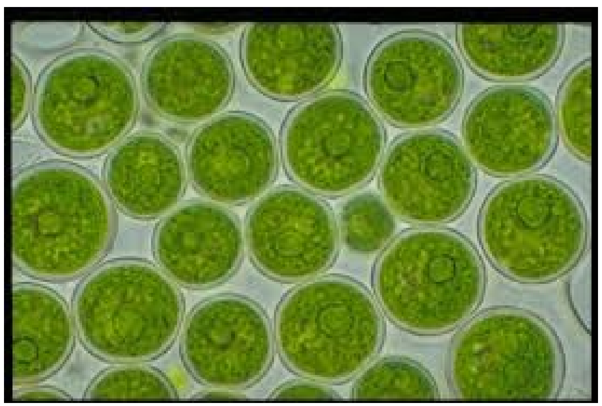
http://megasun.bch.umontreal.ca/protists/chlamy/summary.html

Chlorococcum

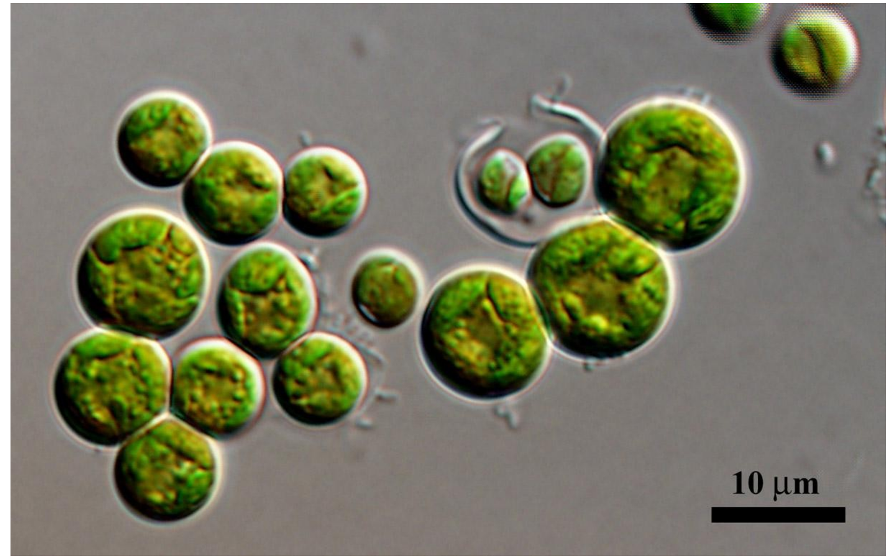


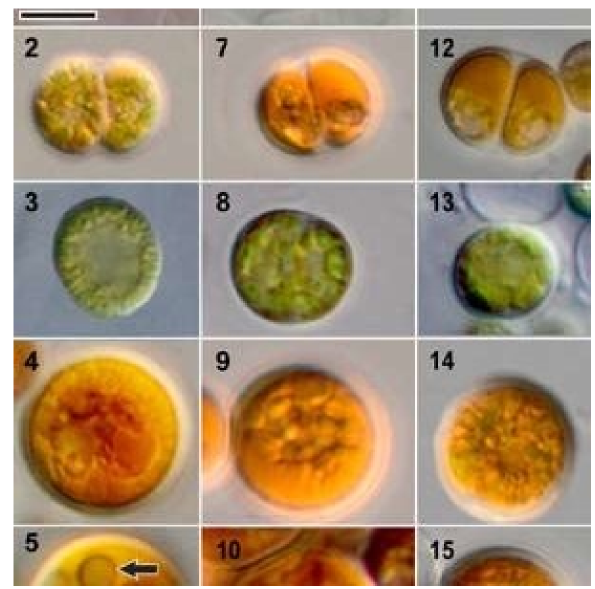
Chlorococcum





Bracteacoccus





often occur in soil

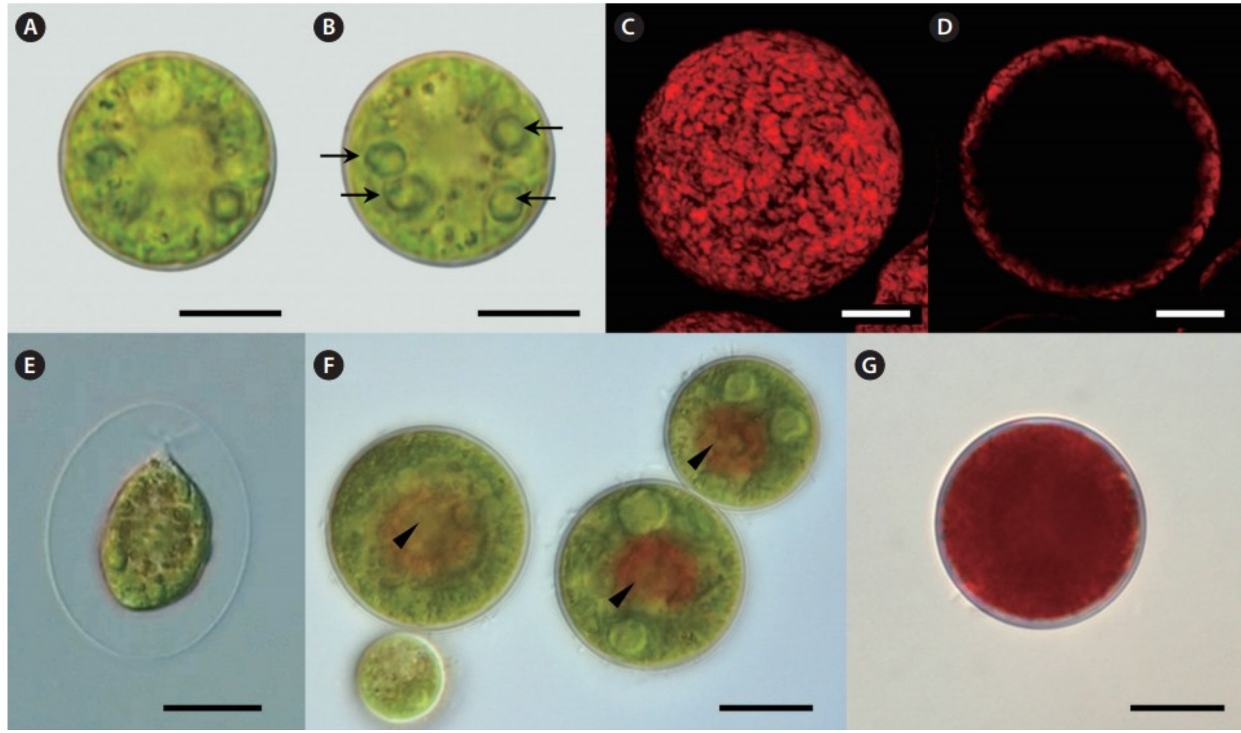
simplified globular morphology

Chlamydomonas-like zoospores

lipidic storage compounds

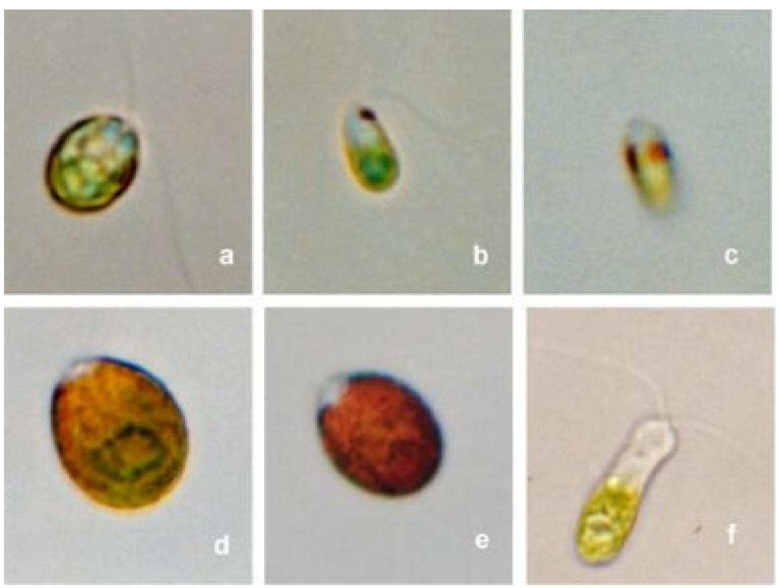
high amounts of carotenoids

Haematococcus



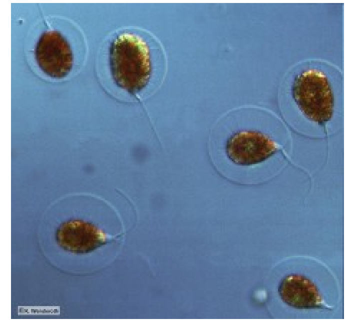
Klochkova et al., 2013, Algae

Dunaliella

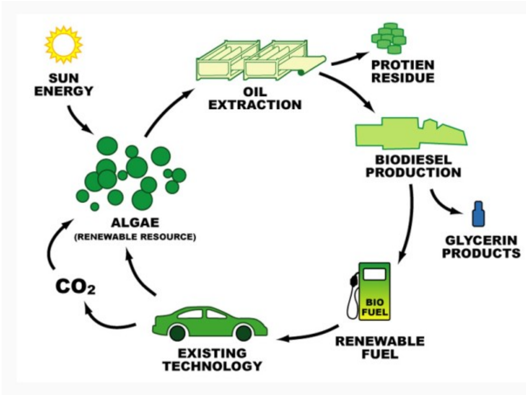


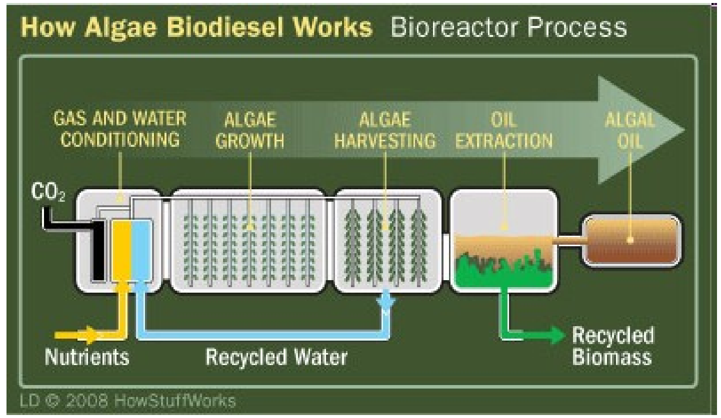
Borowitzka & Siva, 2007, J. Appl. Phycol.

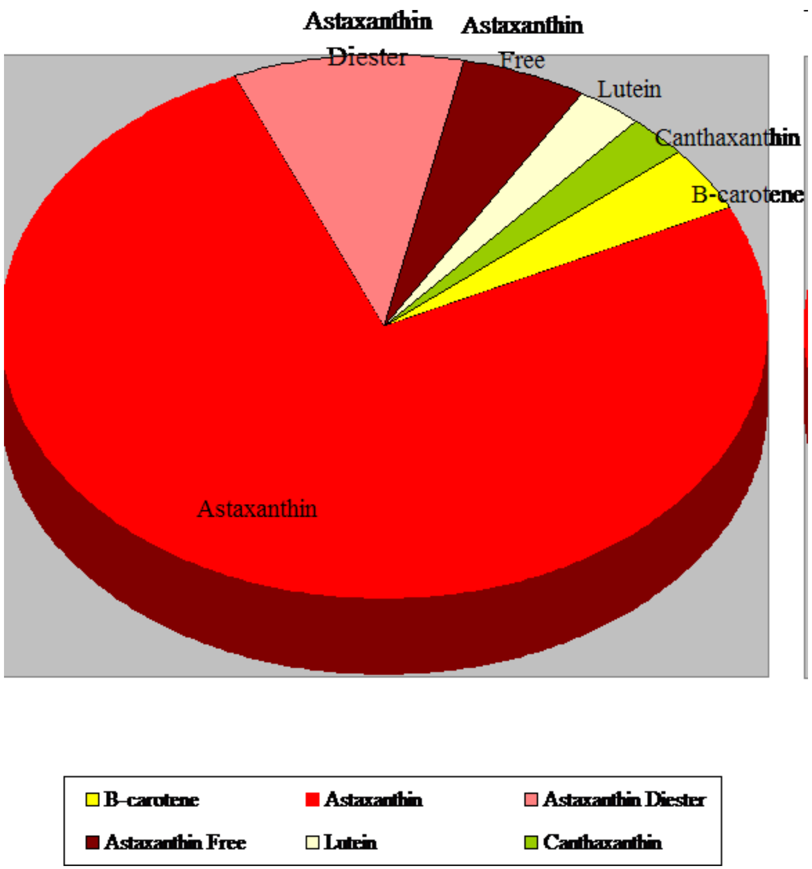
photobioreactores and green algae



Chlorophyceae (Muriellopsis, Dunaliella, Haematococcus),
Eustigmatophyceae (Nannochloropsis), Trebouxiophyceae (Botryococcus)







Haematococcus – composition of carotenoids

http://www.igb.fraunhofer.de/en/competences/environmental-biotechnology/microalgae/astaxanthin.html

http://www.algae-biotech.com/

Algenhaus, Hamburg