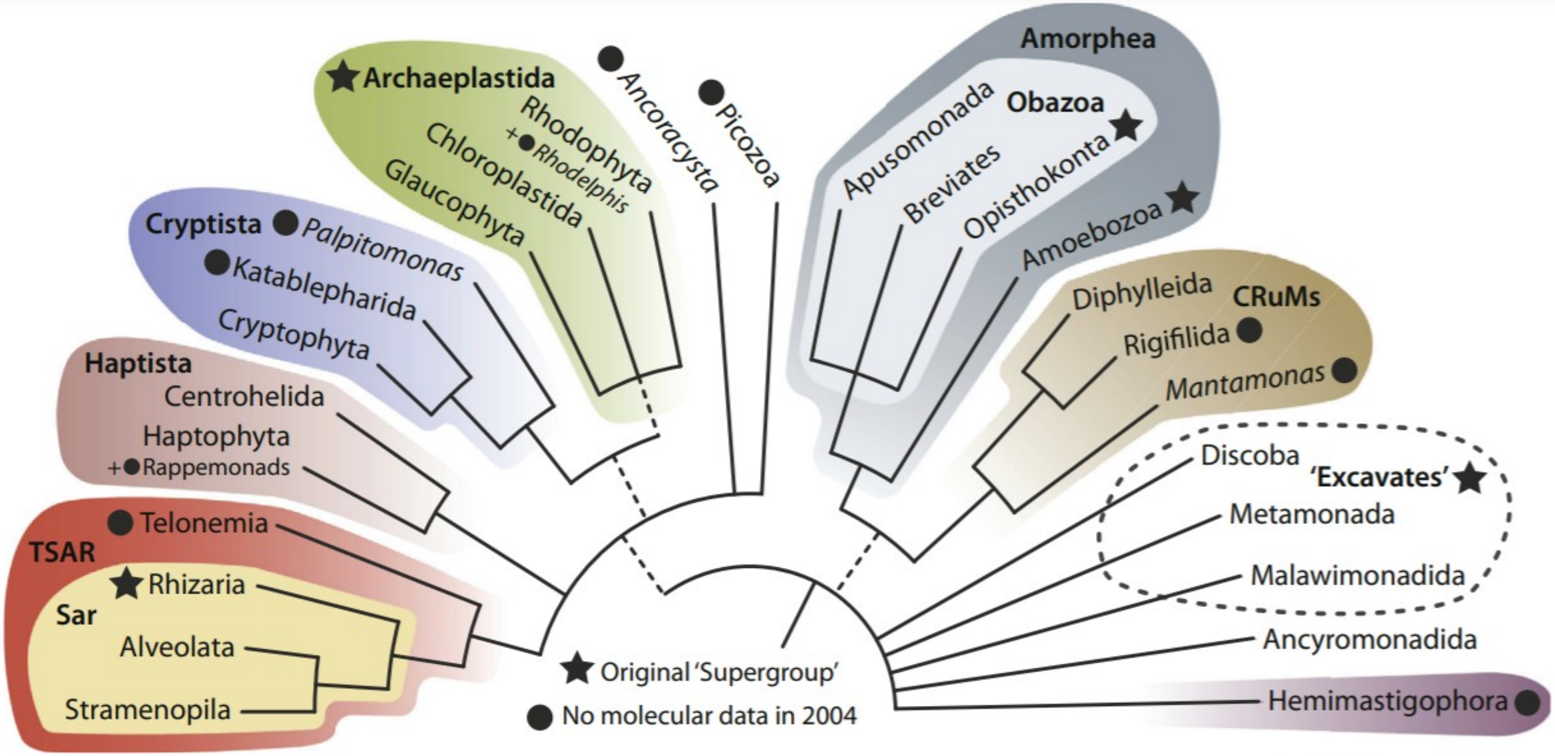
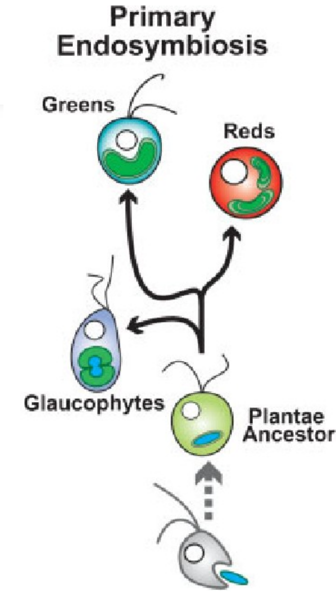
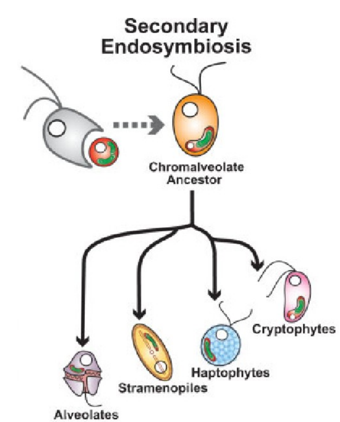


Trends in Ecology & Evolution

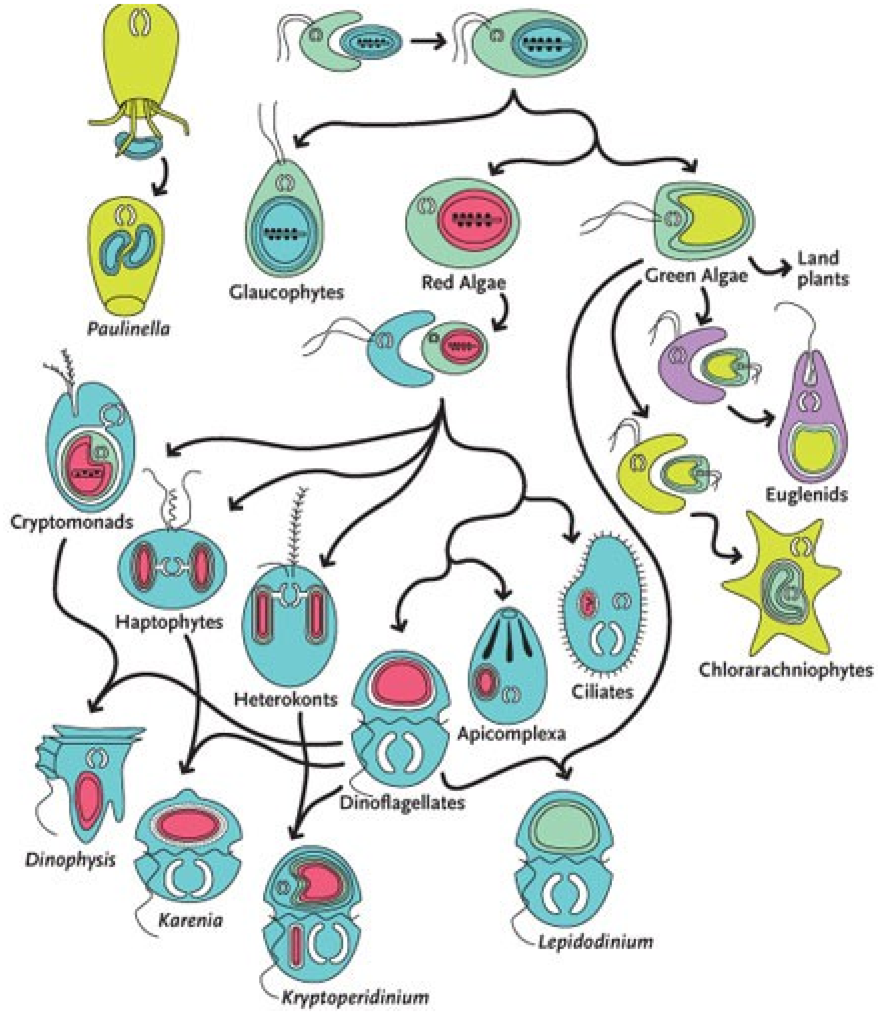
Figure 1. The New Tree of Eukaryotes.

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

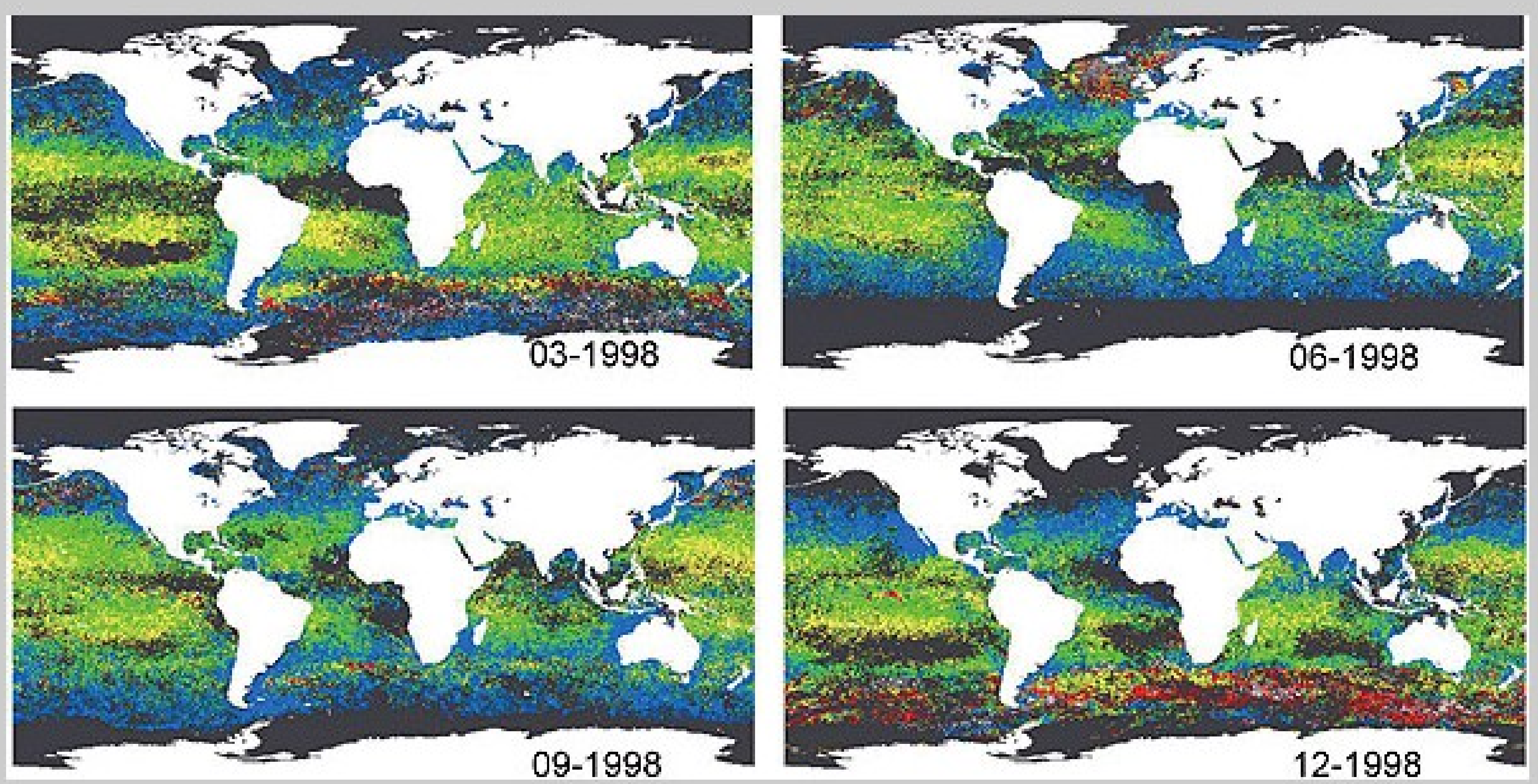


[very sipmlified] scheme of plastid endosymbioses

(more in "Protistology")

oceanic phytoplankton – „basic scheme" of the RECENT 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.



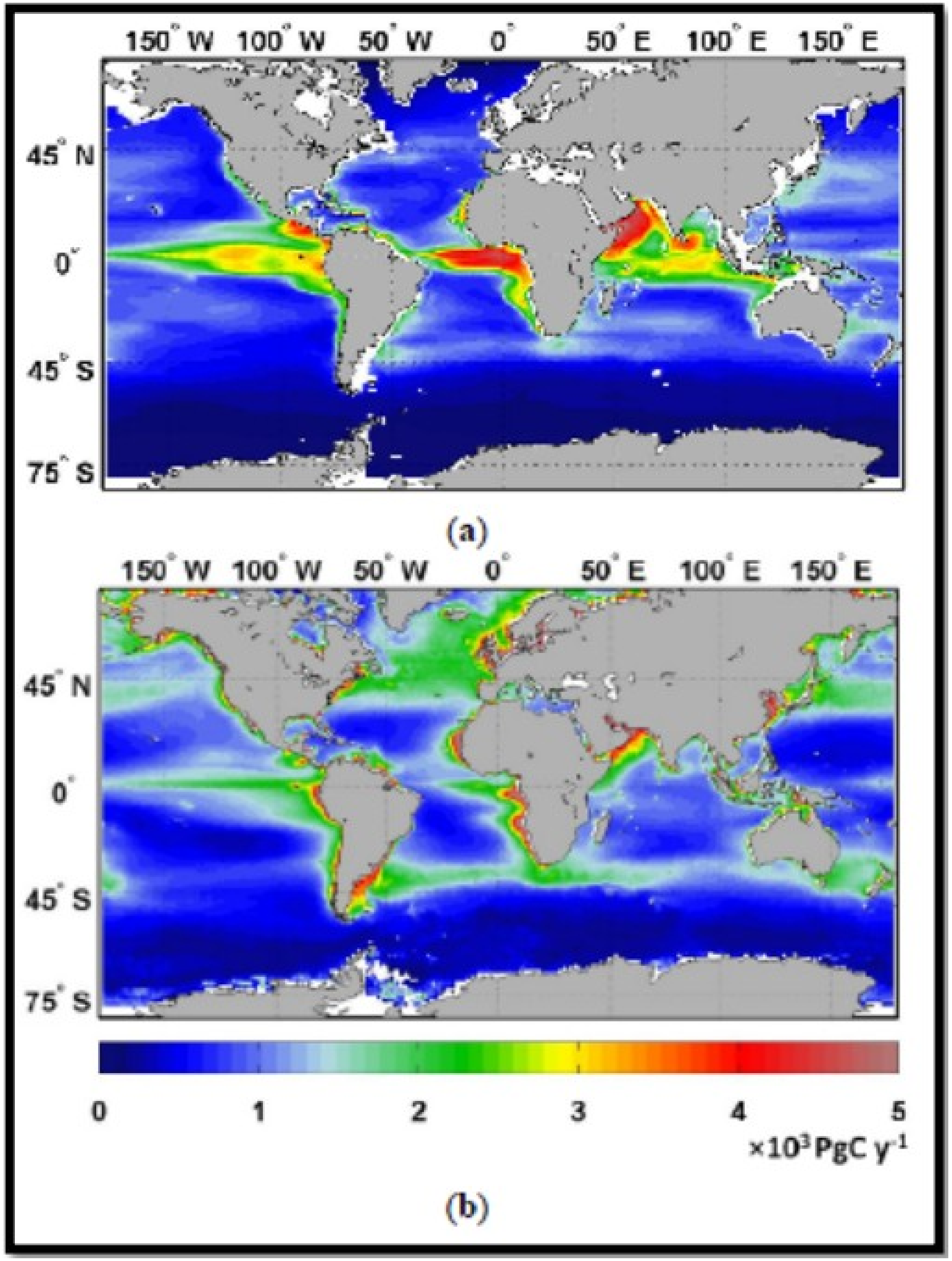
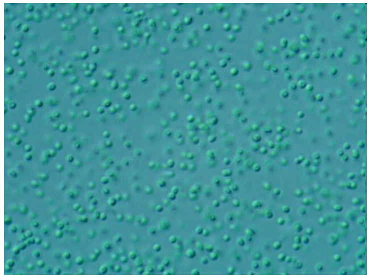


Figure 1. Climatological map Distribution of annual marine NPP for (a) NASA Ocean Biogeochemical Model and (b) Vertically-Integrated Production Model (VGPM) for the period from September 1998 to 2011 (Rousseaux – August 1999 (Blue < 100 g C m^{-2}, Green > 110 g C m^{-2} and < 400 g C m^{-2}, Red > 400 g C m^{-2}) (Rutgers Institute of Marine and Gregg, 2014). Globally, diatoms accounted for about 50 per cent of NPP while coccolithophores, chlorophytes and cyanobacteria accounted for about 20 per cent, 20 per cent and 10 per cent, respectively. Diatom NPP was highest at high latitudes and in equatorial and eastern boundary upwelling systems. Coastal Sciences, http://marine.rutgers.edu/opp/). Coastal ecosystems (red – green) and the permanently stratified subtropical waters of the central gyres (blue) each account for ~30 per cent of the ocean's NPP, whereas the former accounts for only ~8 per cent of the ocean's surface area compared to ~60 per cent for the open ocean waters of the subtropics (Geider et al., 2001; Marañón et al., 2003; Muller-Karger et al., 2005).

lineages with secondary rhodoplasts in marine phytoplankton



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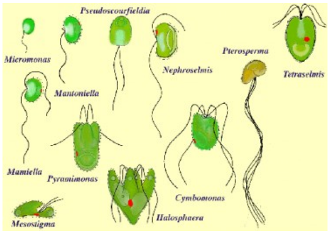
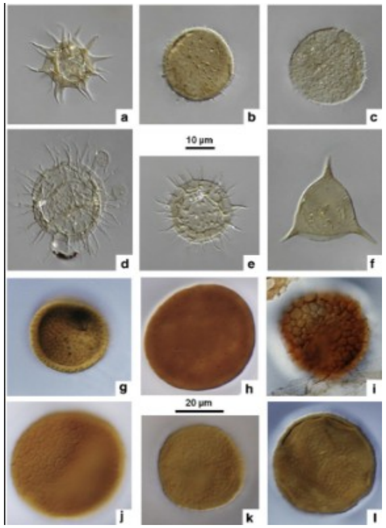
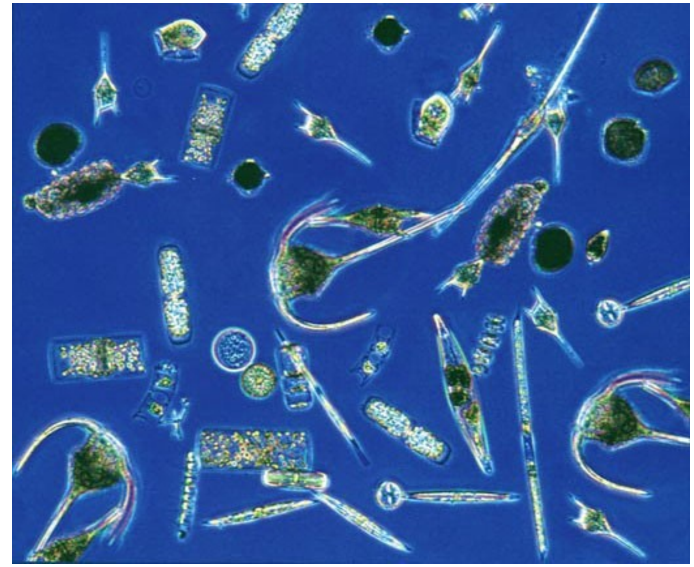
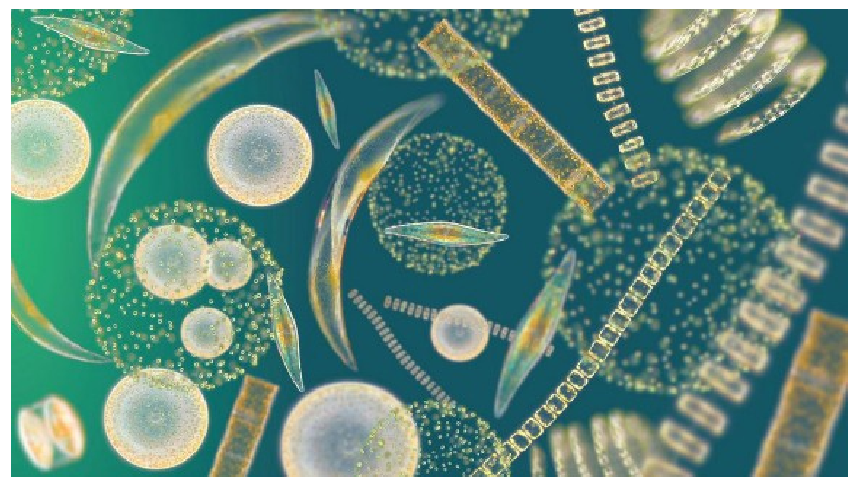


Malone et al. 2016, Primary Production, Cycling of Nutrients, Surface Layer and Plankton

palaeozoic vs. recent marine phytoplankton







Götz & Feist-Burkhardt, 2012, Palaeogeogr, Palaeoclim, Palaeoecol
Le Hérissé et al., 2009, Palynol.

	a = divergence of pigmented heterokonts from the heterotrophic heterokonts	b = divergence of the diatoms
900	582.213 (797.509 - 416.532)	253.429 (348.114 - 193.839)
1200	646.098 (912.334 - 452.653)	268.404 (367.992 - 201.549)
range	646.098 - 582.213 (912.334 - 416.532)	268.404 - 253.429 (268.404 - 193.839)

● Minimum age constraint by fossil record

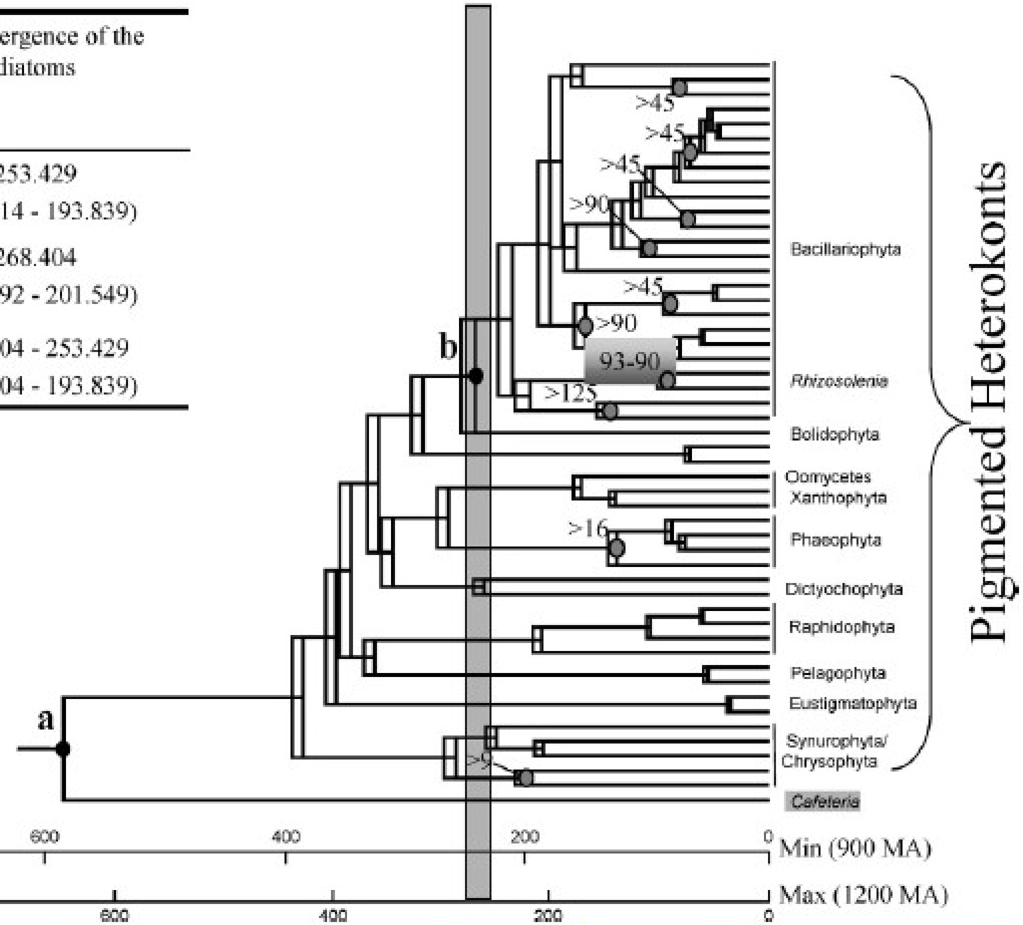


Fig. 2. Molecular timescale for Heterokonta using minimum and maximum inference of the age of the root at 900 Ma (grey) and 1200 Ma (black), respectively (Douzery *et al.* 2004), and with *Rhizosolenia* root constrained to 93 Ma based on biochemical isoprenoid evidence in this genus by Sinninghe-Damsté *et al.* (2004). A grey box indicating the time point of the P/T boundary at 250 Ma as estimated from the minimum and maximum age priors (program constraints as above) is placed over tree. a = origin of the pigmented Heterokonta, b = origin of the diatoms. All time estimates in the table inset are shown with the time as estimated with a 900 or 1200 Ma constraint on the crown group radiation and their standard error. Original data set found in Medlin *et al.* (1997). Heterotrophic taxa are coloured in grey.

Medlin, 2011, Phycologia 50: 684-693

Haptophyta

	a = divergence of the two haptophytes classes	b = diversification of the Prymnesiales
900	708.666 (842.493 - 521.217)	576.603 (717.614 - 407.043)
1200	942.769 (1124.032 - 680.732)	767.039 (956.615 - 529.371)
range	942.769 - 708.666 (1124.032 - 521.217)	767.039 - 576.603 (956.615 - 407.043)

● Minimum age constraint by fossil record

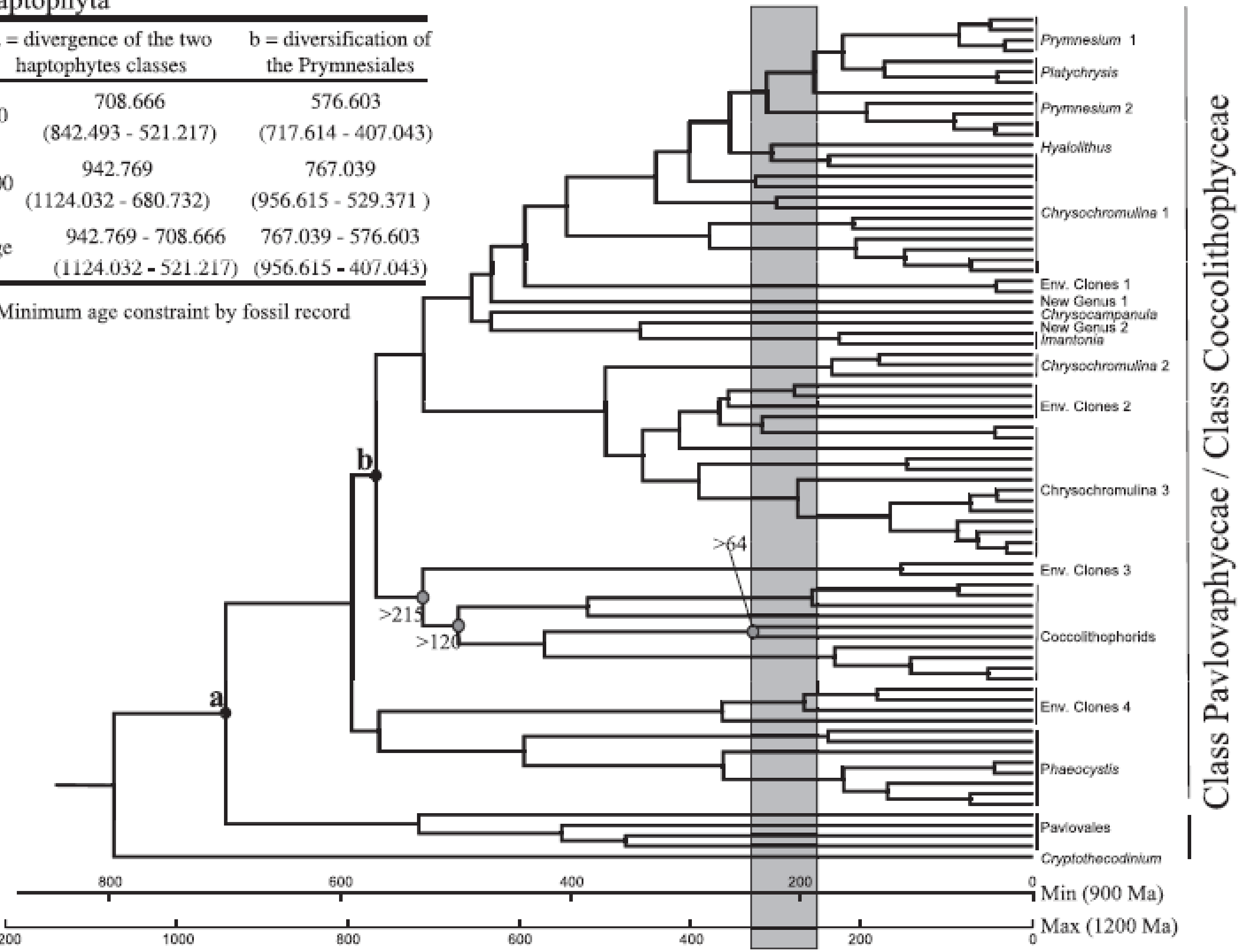
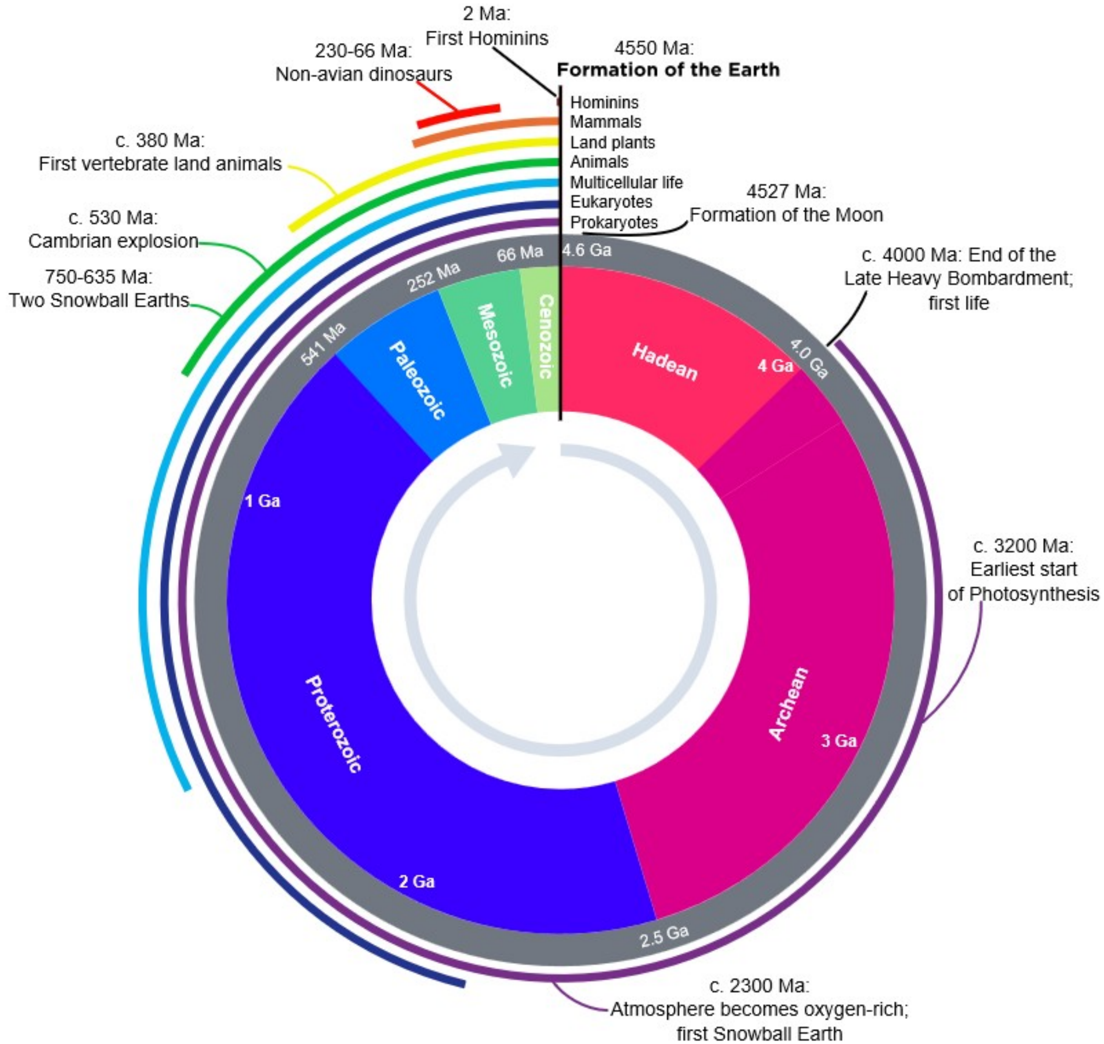
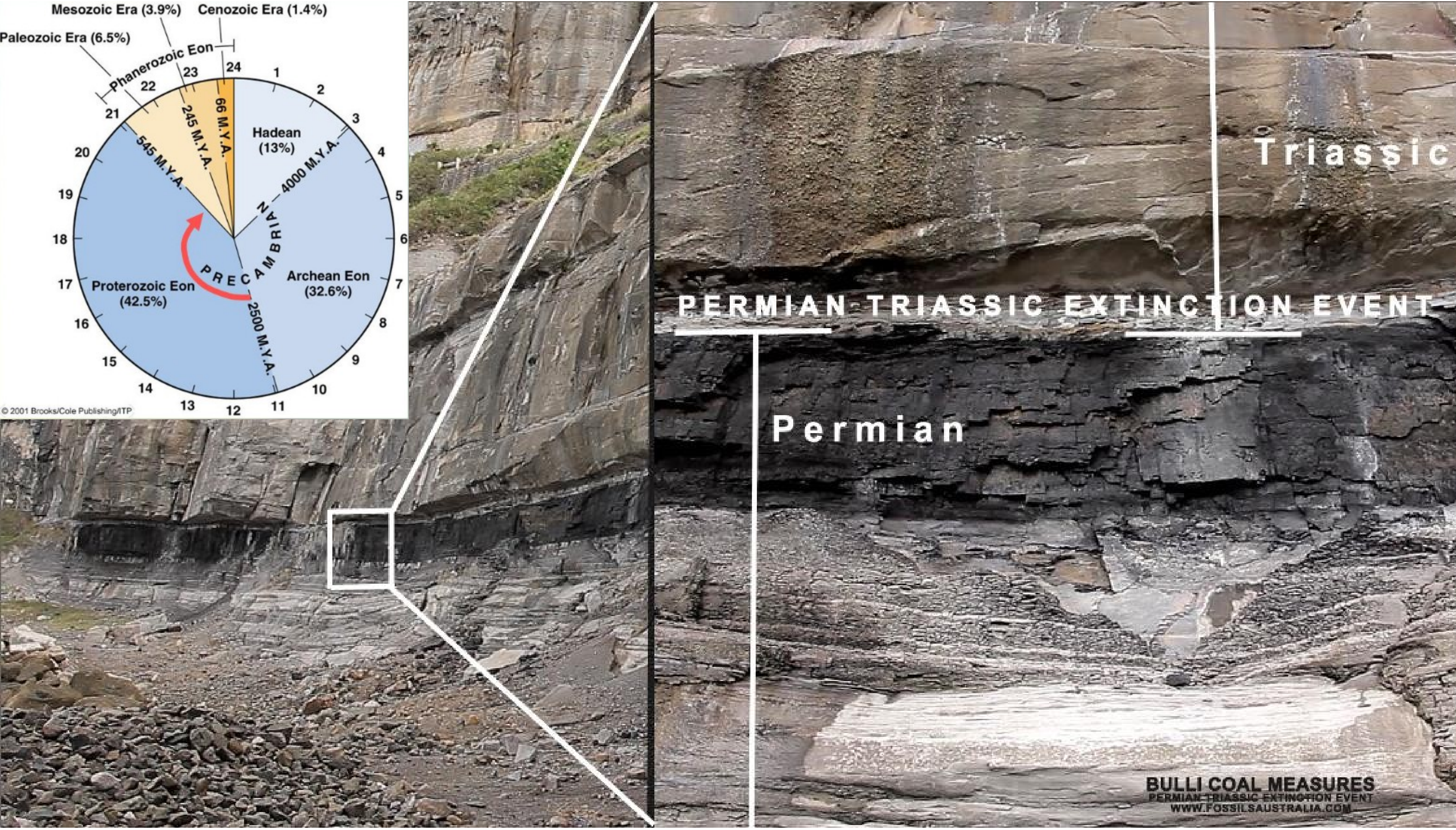


Fig. 3. Molecular timescale for haptophytes using minimum and maximum inference of the age of the root at 900 Ma (grey) and 1200 Ma (black), respectively (Douzery *et al.* 2004). A grey box indicating the time point of the P/T boundary at 250 Ma as estimated from the minimum and maximum age priors (program constraints as above) is placed over tree. a = divergence of the two classes, b = radiation of the order Prymnesiales. All time estimates in the table inset are shown with the time as estimated with a 900 or 1200 Ma constraint on the crown group radiation and their standard error. Original data set found in Edvardsen and Medlin (2007). Heterotrophic taxa are coloured in grey.

Medlin, 2011, Phycologia 50: 684-693



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

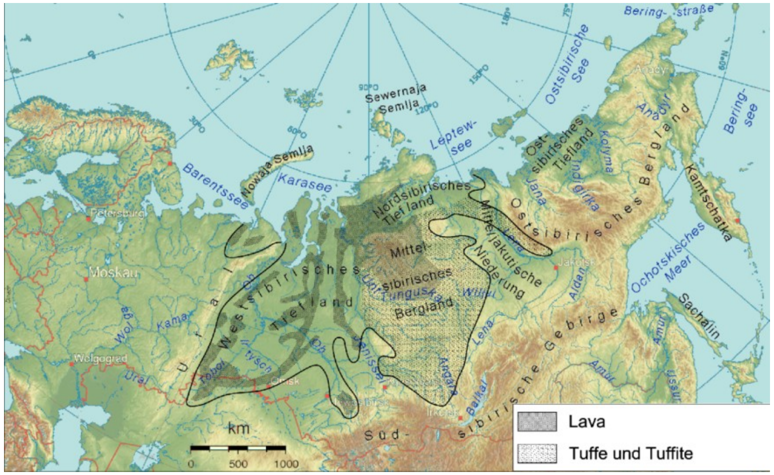


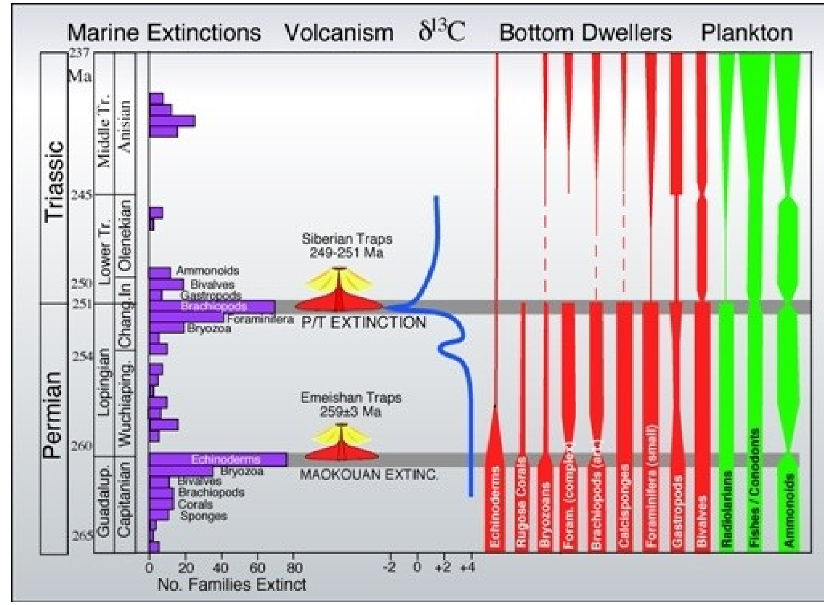
classical geological boundary Proterozoikum vs. Mesozoikum

- dramatic decline of diversity (oceans > continents)
- extinction of multiple high-order lineages – including apparent algal/protist groups
- dramatic fluctuation in sea level
- fluctuations in global temperature
- jumps in primary productivity (ratio of C12/C13)
- changes in basic features of rivers (braided vs. meandering)
- long-term change in vegetation patterns
- acidification of oceans and strong increase in their oxygen limitation / anoxia
- increase in athmospheric CO2, decline in oxygen concentration

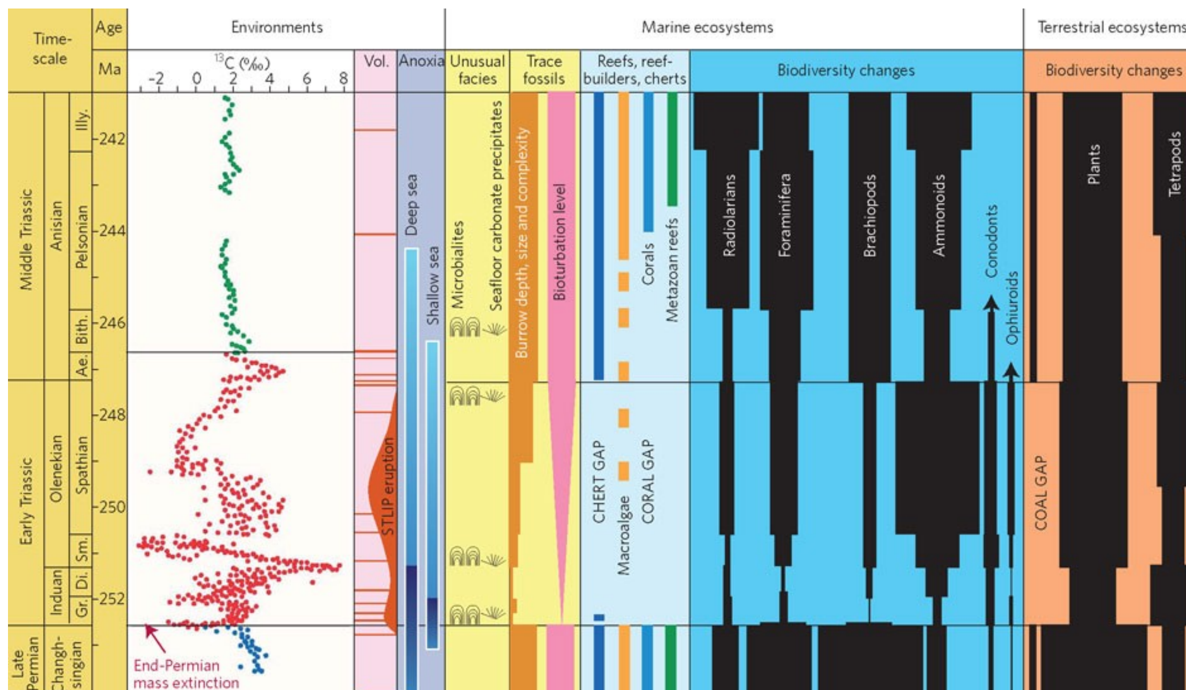
recent estimates of time scale: between 251.941 ± 0.037 and 251.880 ± 0.031 My

Burges, 2014, Nature 111

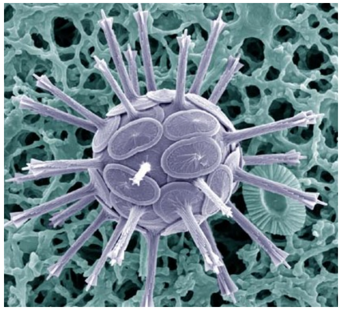




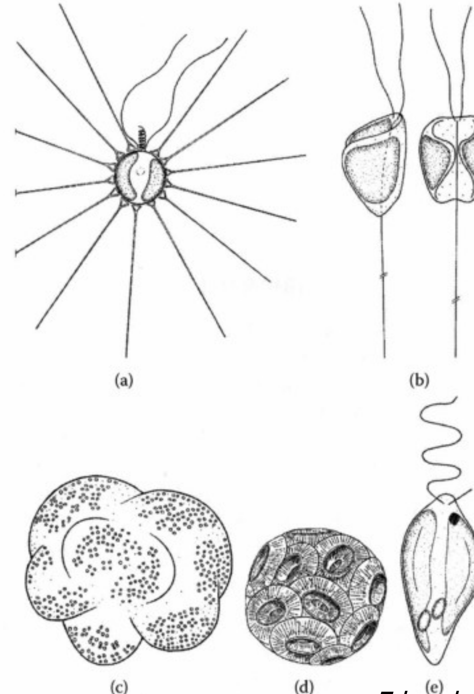
Siberian traps



Haptista - Haptophyta

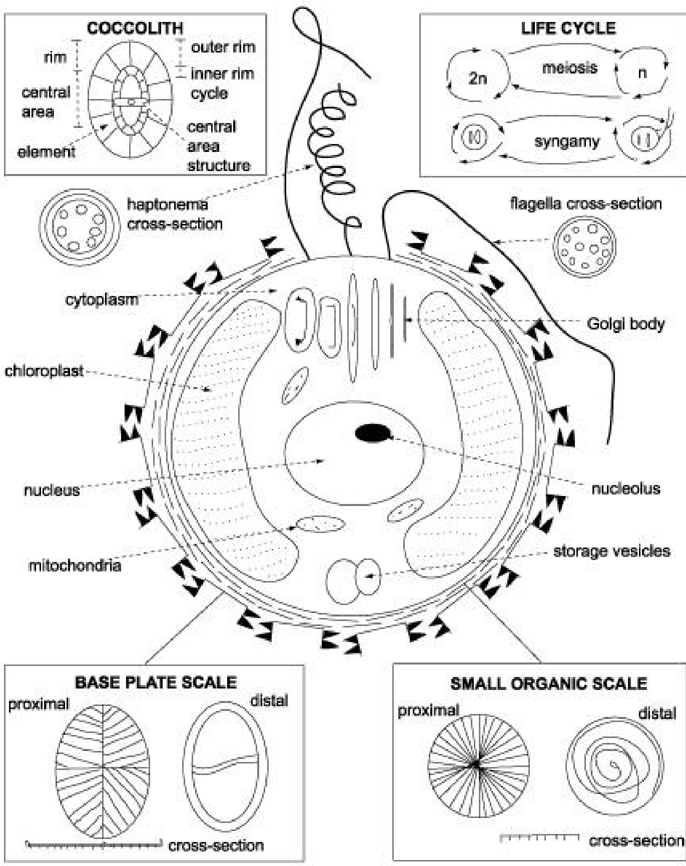


haptonema



Edvardsen & Medlin, 2007

FIGURE 10.1 Haptophytes: (a) *Chrysochromulina hirta*, (b) *Chrysochromulina alifera*, (c) *Phaeocystis pouchetii* colony, (d) *Coccolithus pelagicus*, and (e) *Pavlova gyrans*. (From Throndsen, J., Hasle, G.R., and Tangen, K., *Norsk kystplanktonflora*, Almater Forlag AS, Oslo, 2003. With permission.)



Diagrammatic cross-section of a coccolithophore cell and cell-wall coverings

Above diagram from Bown,P.(Ed.), 1998, Calcareous Nannofossil Biostratigraphy. Chapman and Hall.

lineage including organisms with key effects on global ecosystem (carbon cycle, dimethylsulfide);

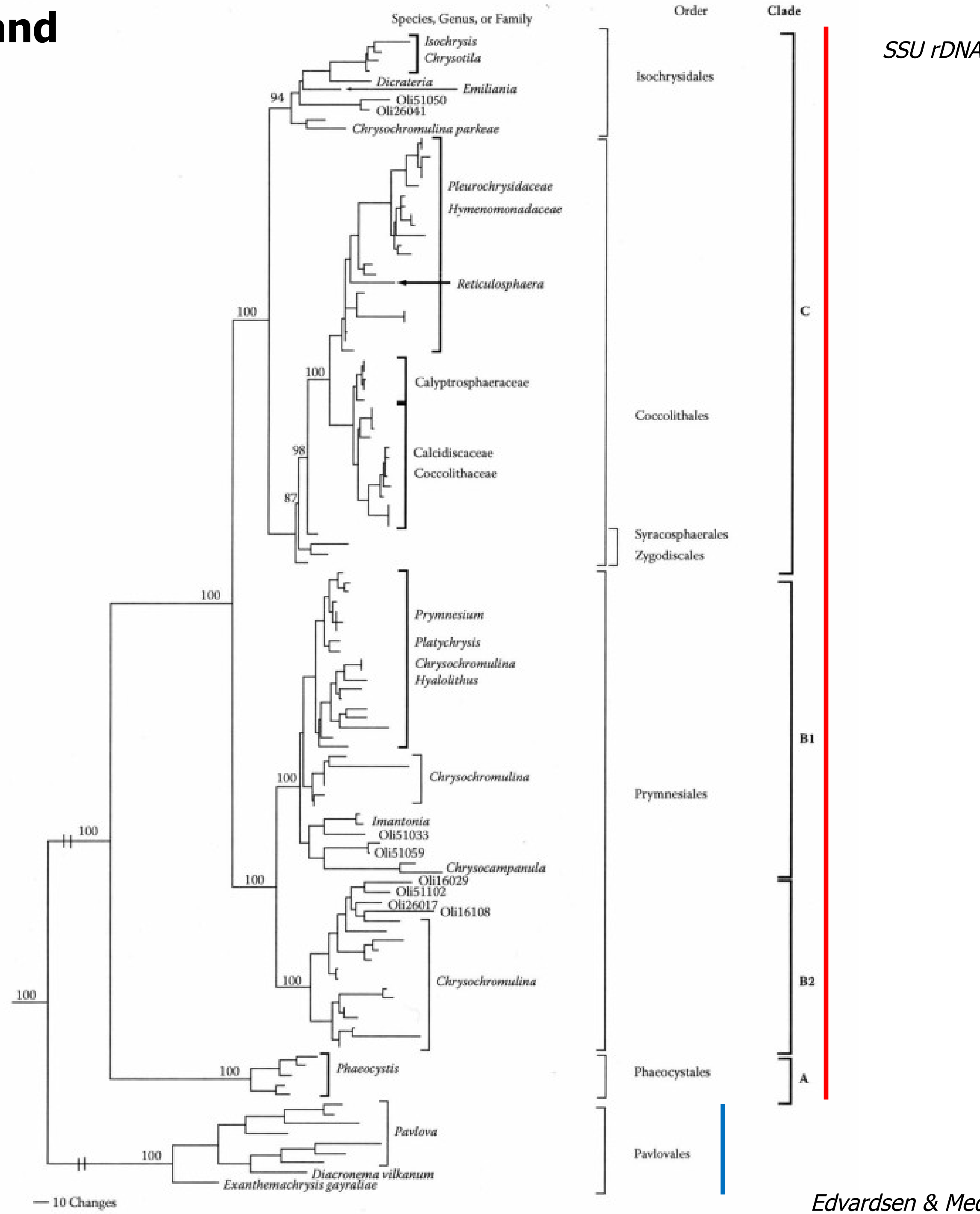
ca 300 recent species, only about 15 species in freshwater [incl. *Corcontochrysis noctivaga]*

some marine and brackish taxa produce toxins (e.g. *Prymnesium* – fish poisoning)

Scyphosphaera
(biomarks.eu)

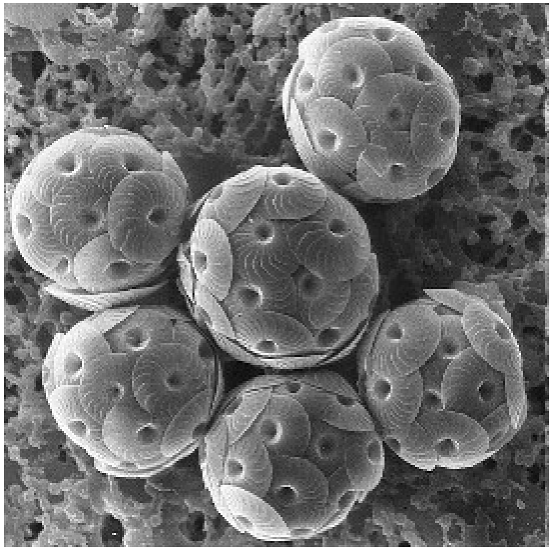
Haptophyta – phylogeny and systematics

Pavlovophyceae
Coccolithophyceae



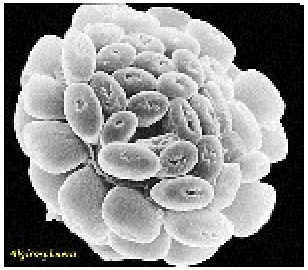
Edvardsen & Medlin, 2007

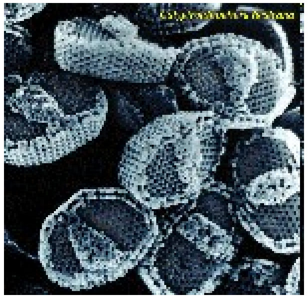
Coccolithales

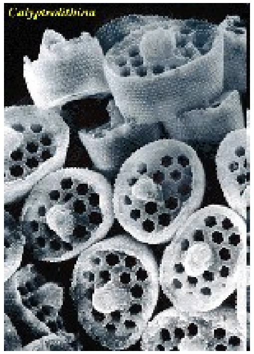


coccoliths – calcium carbonate scales on cellular surface

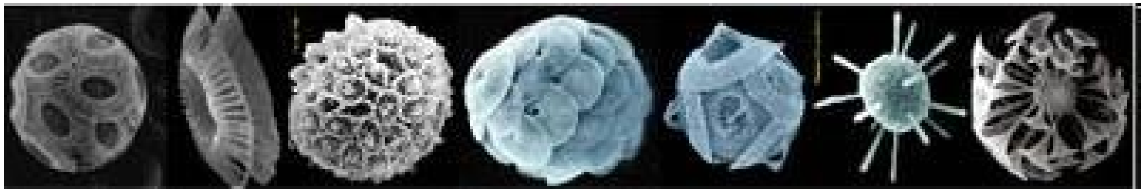
holococcoliths – develop externally on cells







heterococcoliths – develop inside the cells, complex 3D shapes



calcification: $2\ HCO_3^- + Ca^{2+} = CaCO_3 + CO_2 + H_2O$

haptophytes make up about 50% of total inorganic carbon pump in the oceans

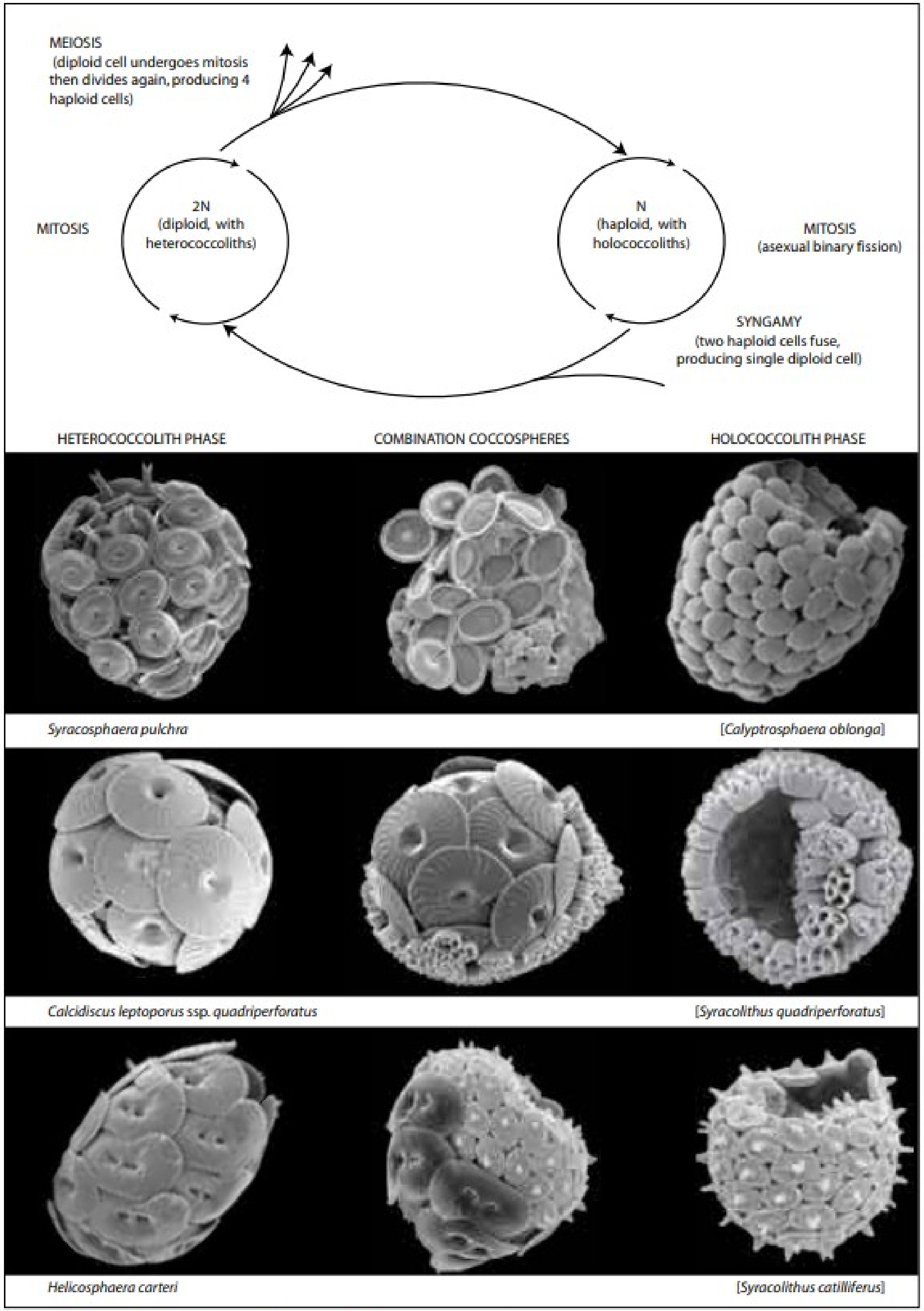
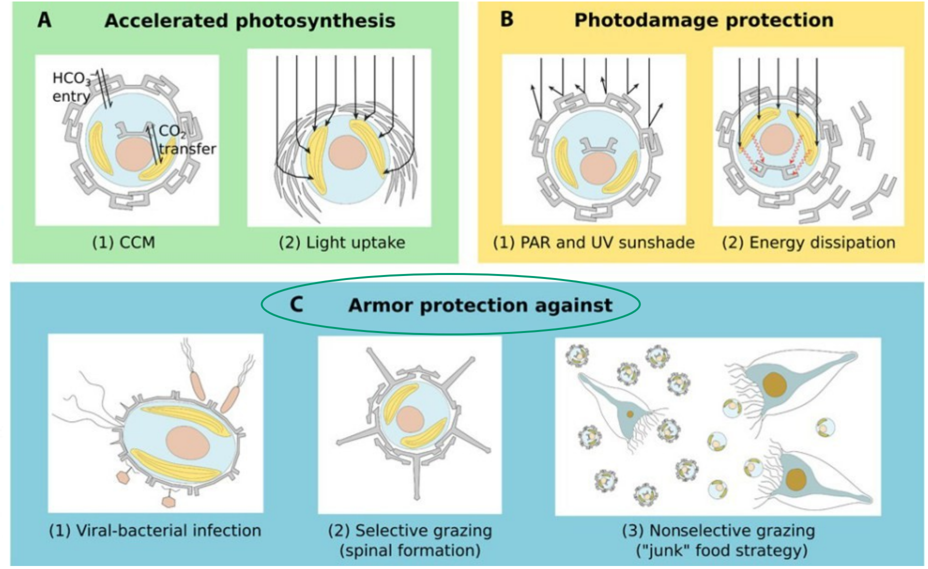
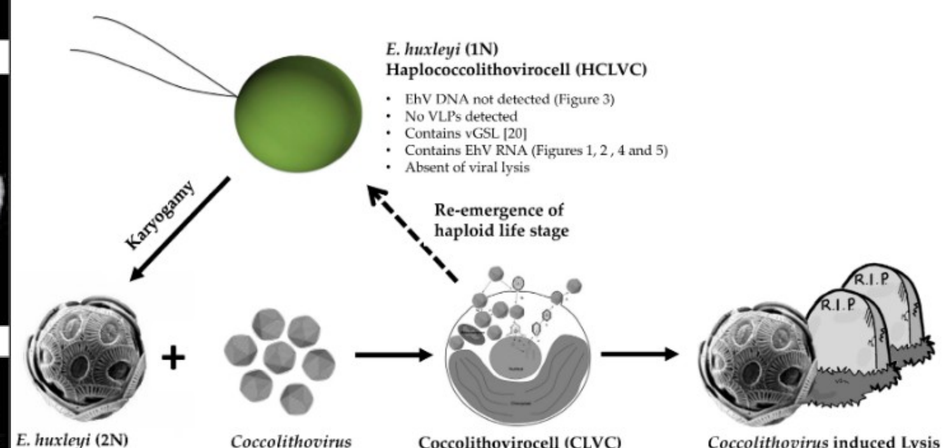


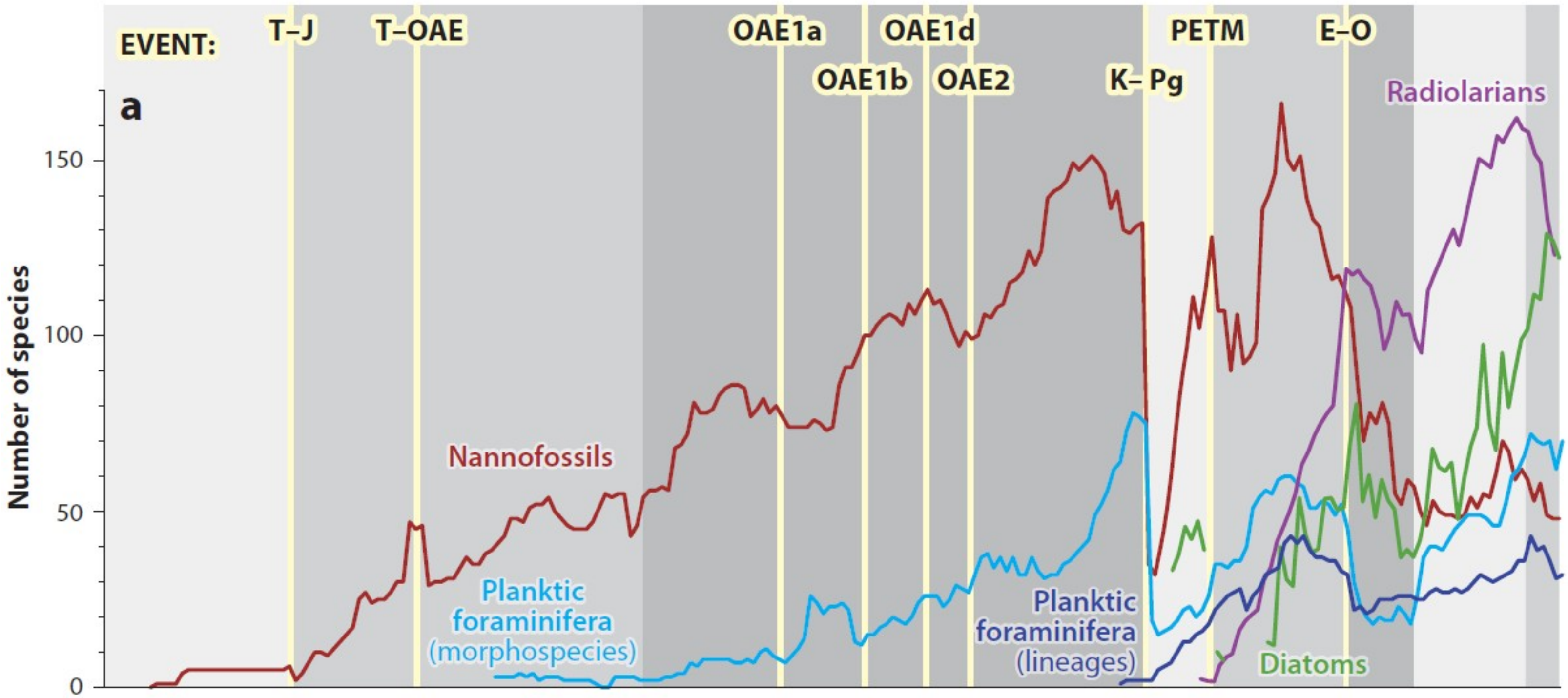
Figure 2 - Typical coccolithophore life-cycle, and three examples

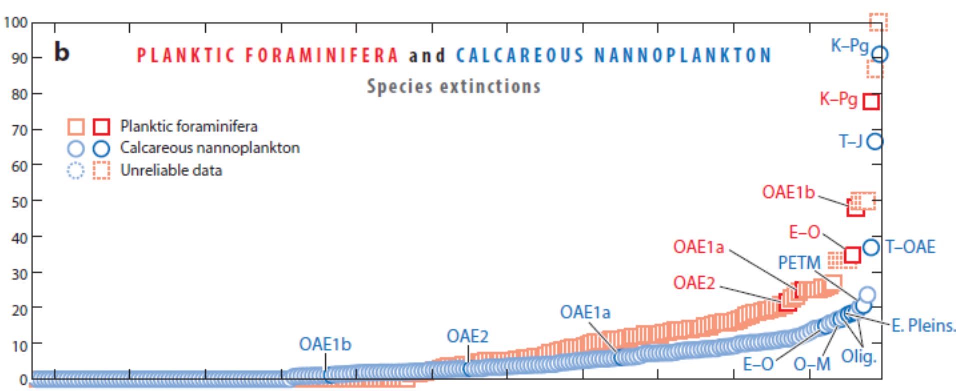


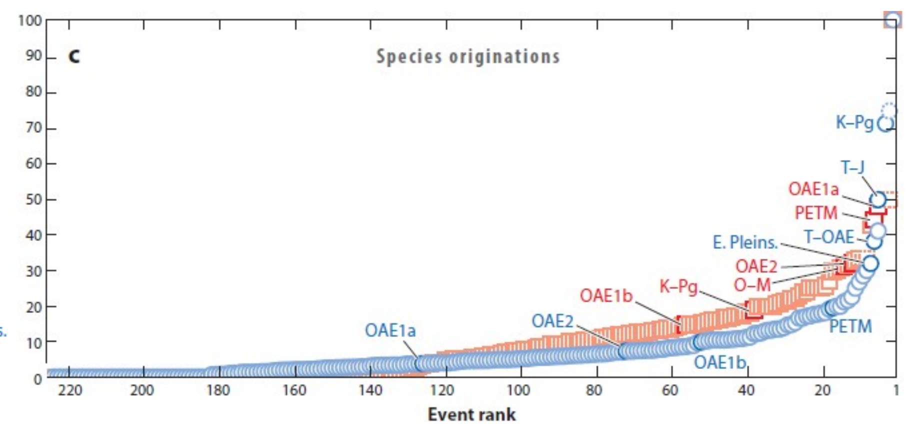


Young et al., 2003, Journal of Nannoplankton Research
Mordecai et al., 2017, Viruses
Anderson, 2016, Oceanbites

Evolutionary patterns of diversity in major marine phytoplankton groups



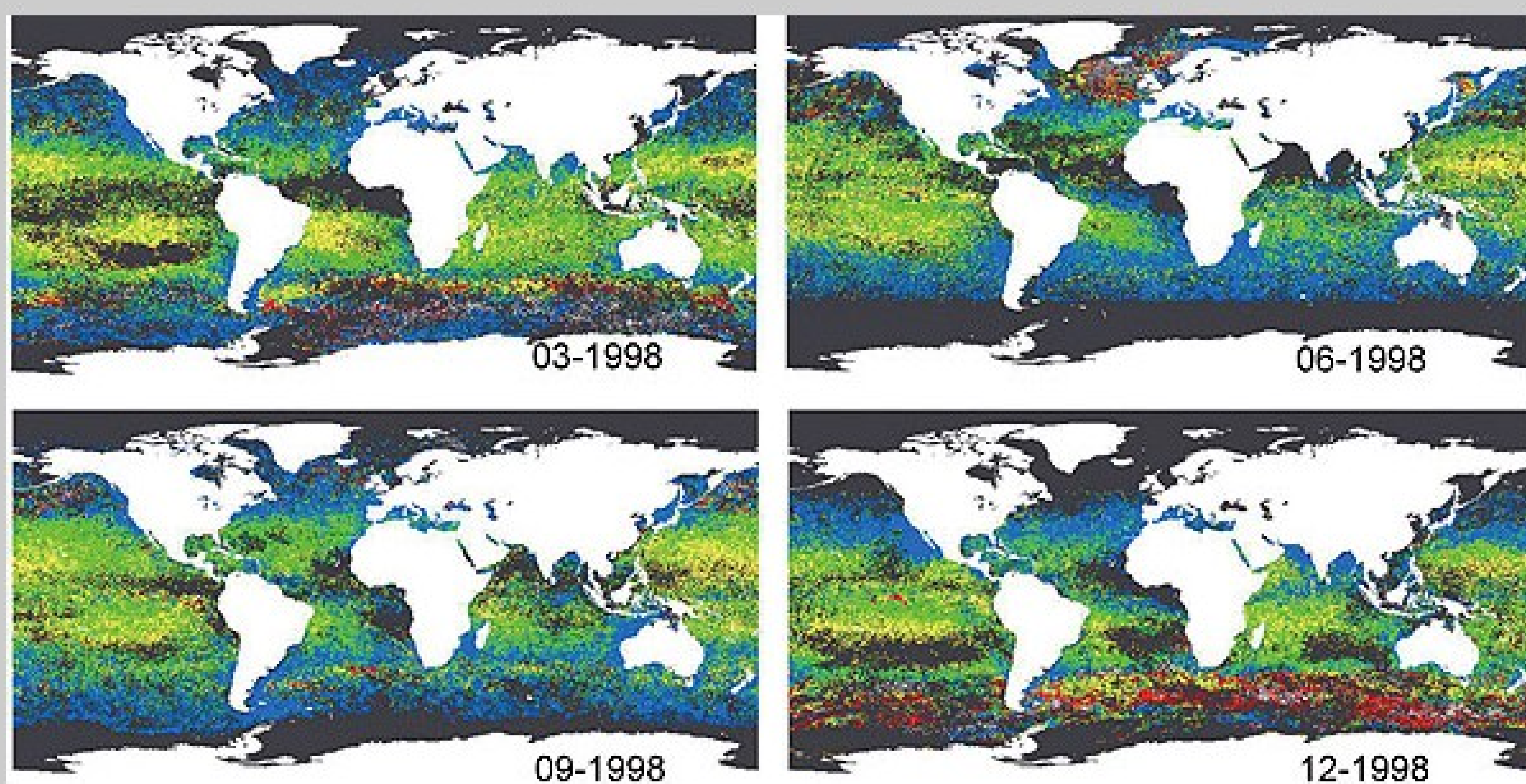




Lowery et al. 2020, Ann. Rev. Earth Pl. Sci

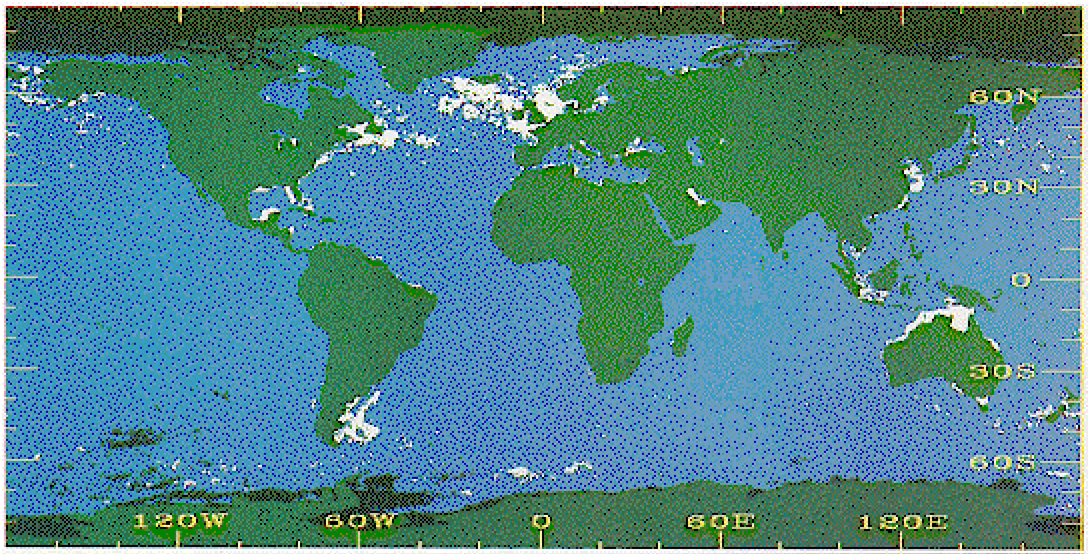
oceanic phytoplankton – „basic structure"

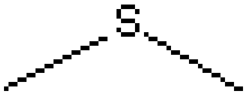
Figure 3 - Variations saisonnières des peuplements de phytoplancton (en bleu : haptophytes; en vert : Prochlorococcus; en jaune : Synechococcus; en rouge : diatomées). Les diatomées abondent au printemps aux hautes latitudes, où les haptophytes dominent le reste de l'année. Prochlorococcus et Synechococcus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

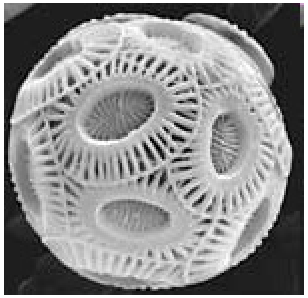


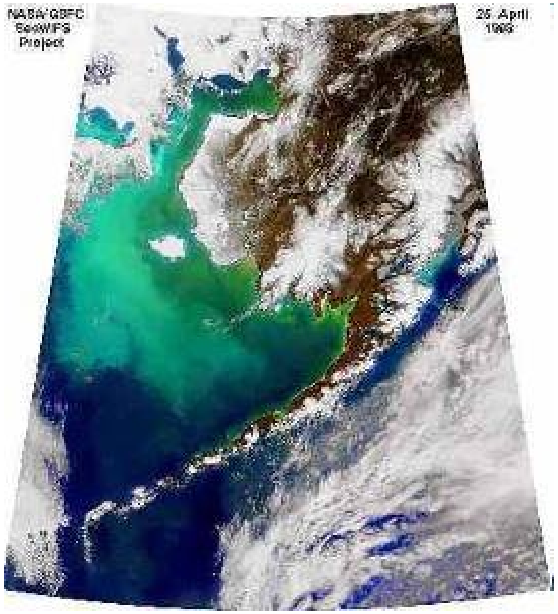
white tides

and - dimethylsulfide - source for the condensation nuclei of clouds

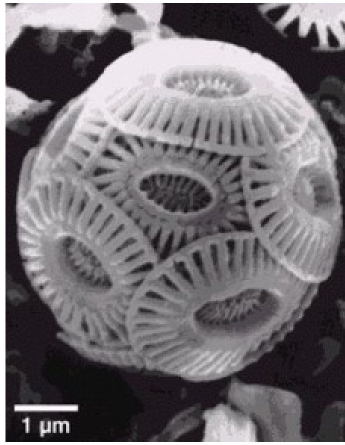


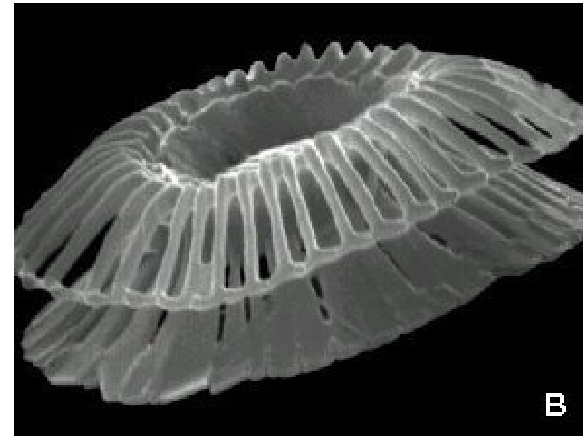


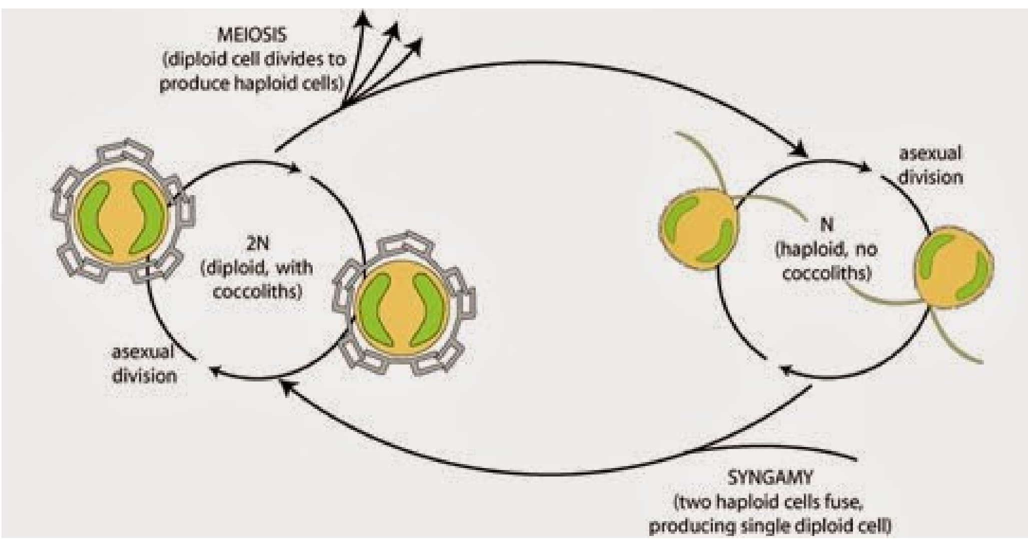




Emiliania huxleyi – one of the most frequent recently occurring eukaryots on Earth







E. hux. is evolutionarily very young – only since Pleistocene

Emiliania huxleyi (Isochrysidales, Noelaerhabdaceae)

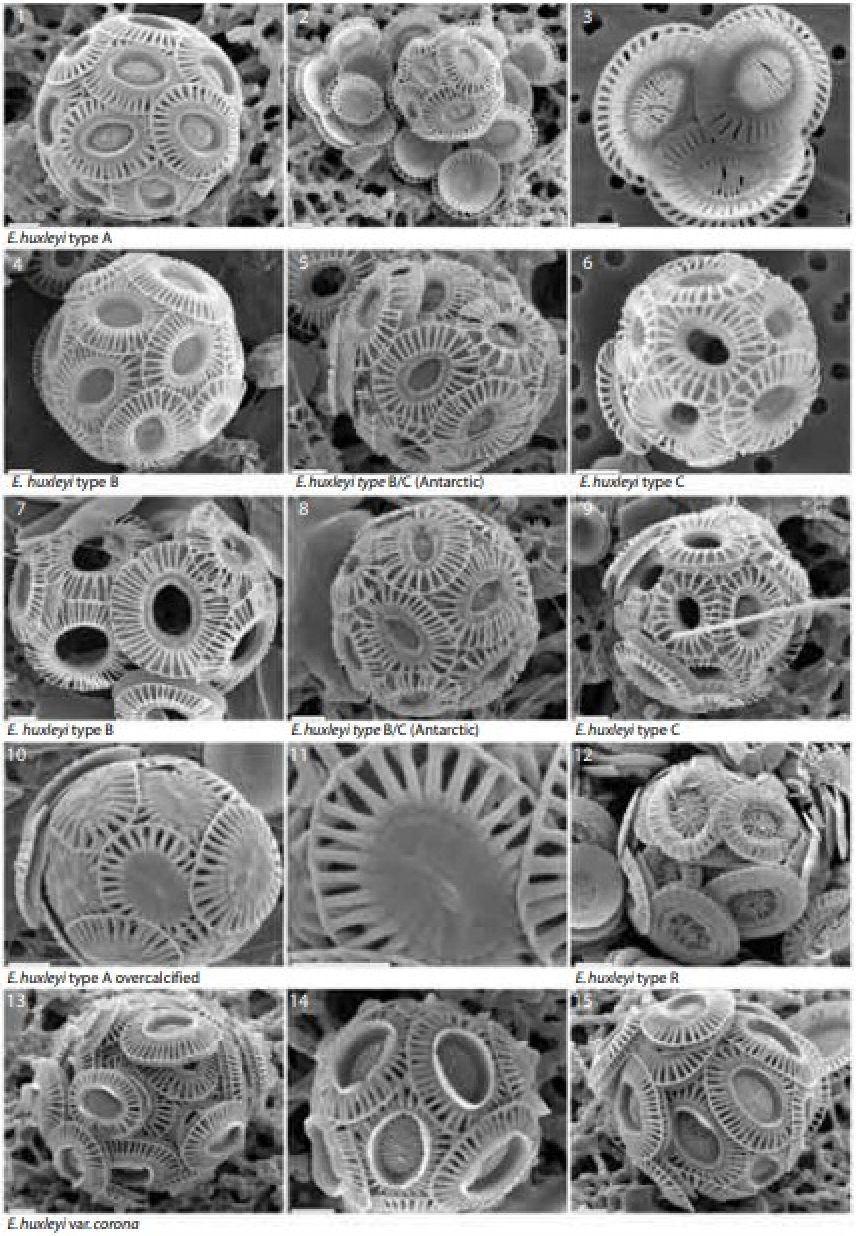
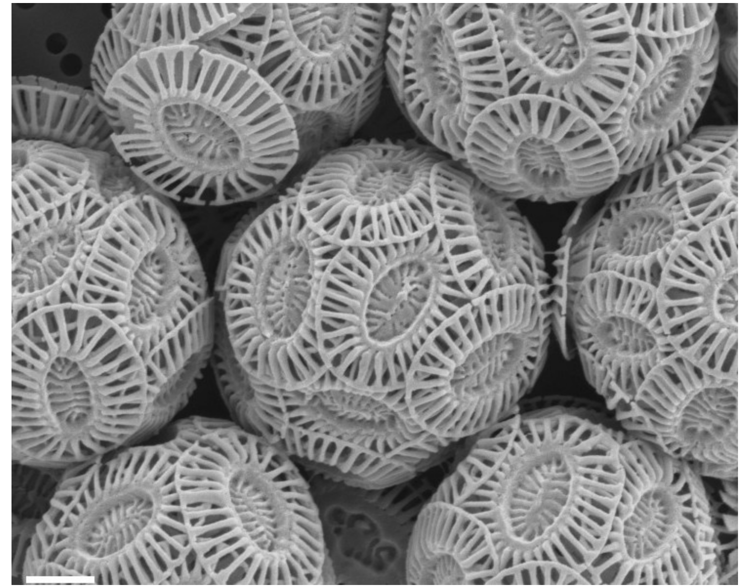


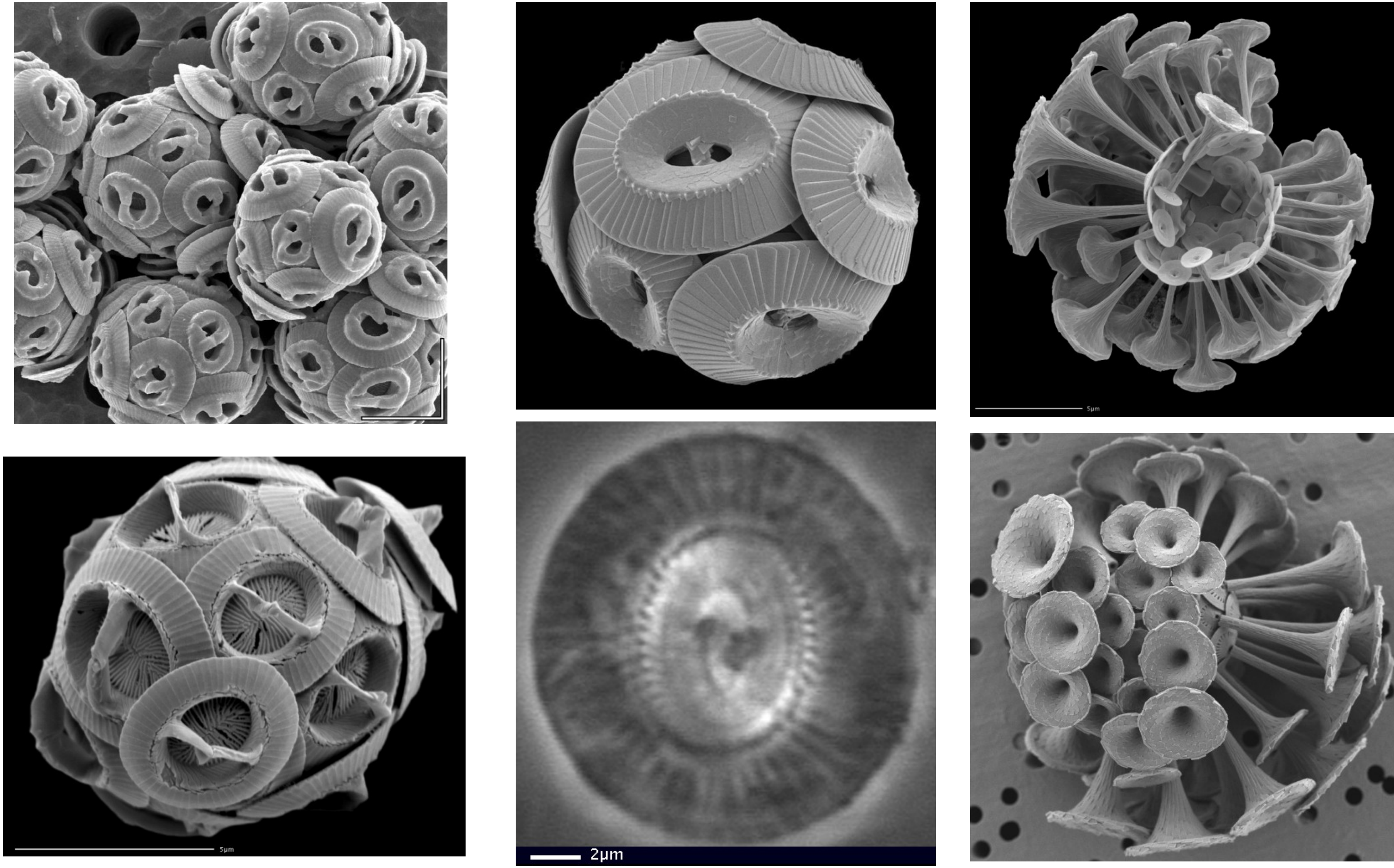
Plate 1 - Noelaerhabdaceae: *Emiliania*



E.hux type A

E.hux type B

Young et al., 2003, Journal of Nannoplankton Research; http://www.mikrotax.org/Nannotax3/



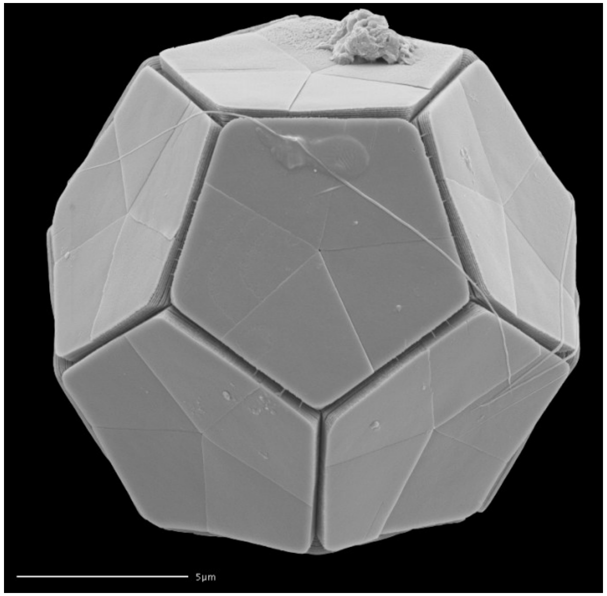
Gephyrocapsa oceanica Coccolithus pelagicus Discosphaera tubifera

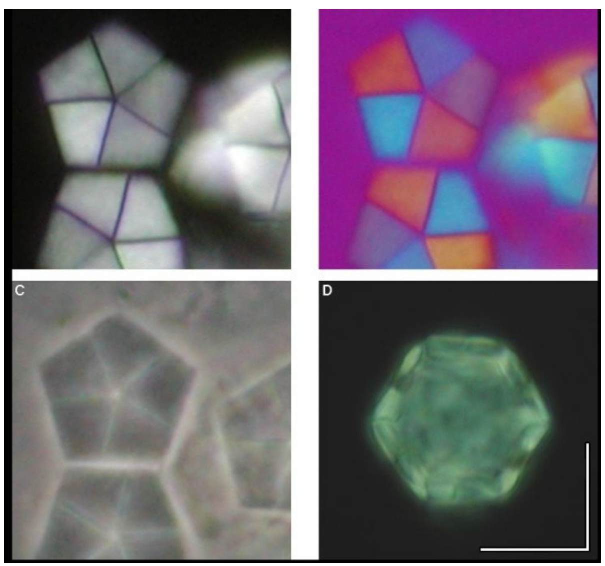
(Isochrysidales, Noelaerhabdaceae) (Coccolithales, Coccolithaeae) (Syracosphaerales,
Rhabdosphaeraceae)

- 7.3 my to recent - 66 my to recent - 16 my to recent

Young et al., 2003, Journal of Nannoplankton Research
http://www.mikrotax.org/Nannotax3/

Braarudosphaerales





Braarudosphaera bigelowii
(Braarudosphaeraceae)
- 100.5 my to recent

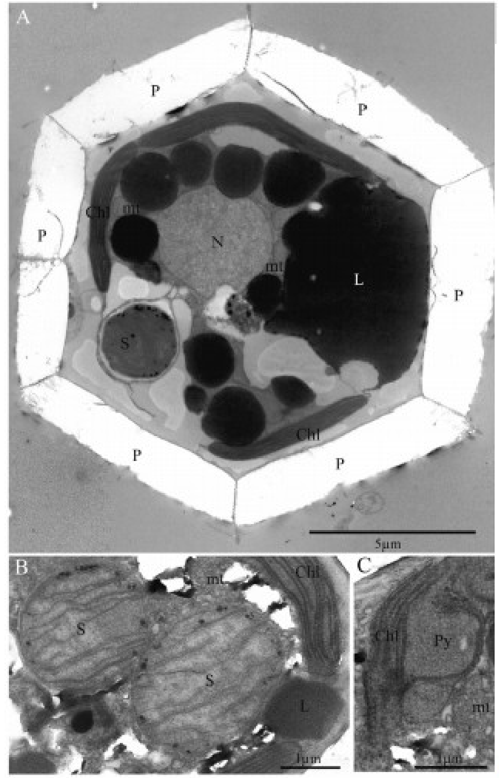


Figure 2. TEM images of *Braarudosphaera bigelowii* specimens -A and -B. (A) *B. bigelowii* specimen-B from offshore Tomari port, Tottori, showing nucleus (N), chloroplasts (Chl), lipid globules (L), pentaliths (P), mitochondria (mt) and spheroid body (S). (B) *B. bigelowii* specimen -A from Tosa Bay, Kochi, Japan, showing detail of spheroid bodies (S). Note that the structure contains about 10 lamellae. The chloroplast (Chl) and lipid globules (L) can also be seen. (C) Detail of chloroplast of *B. bigelowii* specimen -A from Tosa Bay, Kochi, Japan, showing a bulging type of pyrenoid (Py). The mitochondrial profile (mt) can be seen.
doi:10.1371/journal.pone.0081749.g002

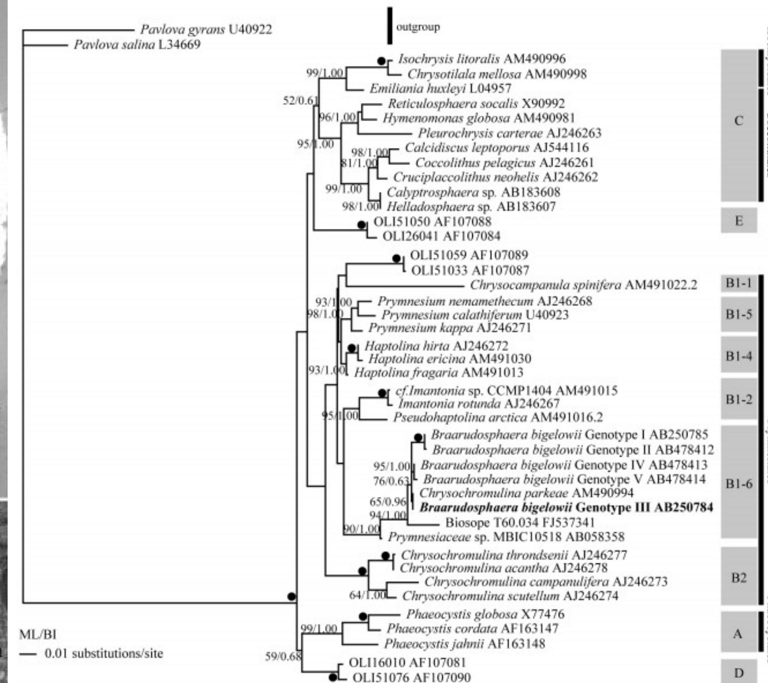
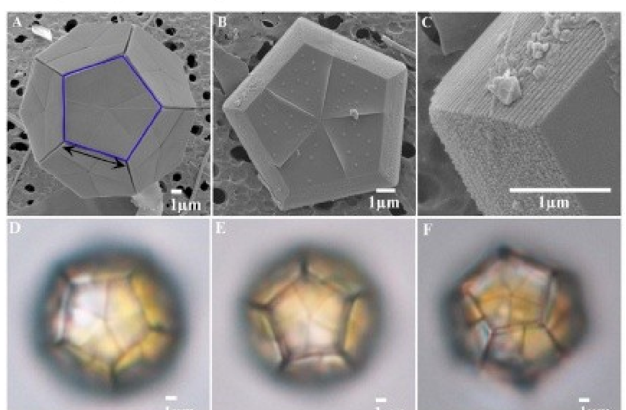


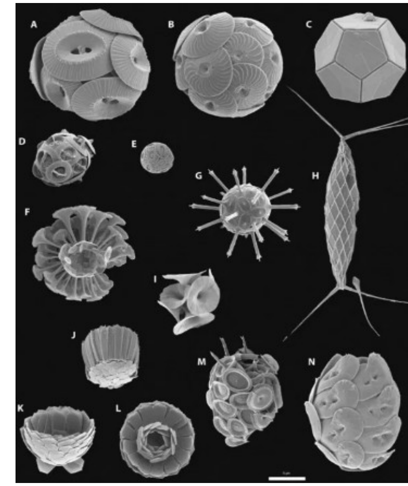
Figure 4. Phylogenetic tree based on 18S rDNA sequences using the Maximum Likelihood method. Representatives of the Pavlovophyceae were used as an out-group. Asterisks refer to the clade names of Edvardsen et al. [24]. The numbers on each node indicate the bootstrap values from ML analysis and posterior probability of BI analysis. Solid circles indicate the clades supported by very high bootstrap values (100%) and posterior probability (1.00) by all analyses (ML, NJ, MP, and BI).
doi:10.1371/journal.pone.0081749.g004

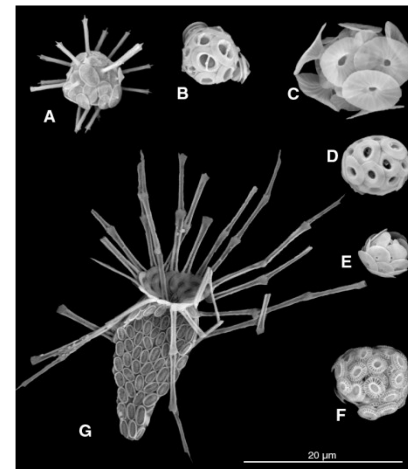


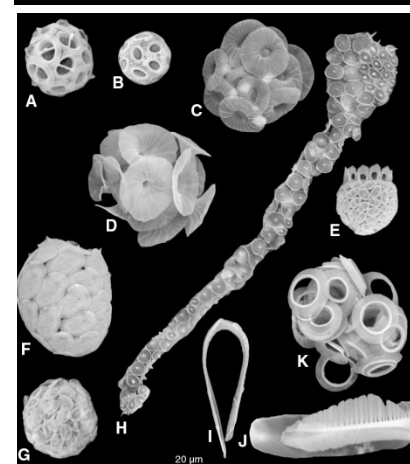
- an old lineage (since Mesozoic)
- coccoliths develop extracellularly (i.e. probably not homological with other groups)
- probably belongs to Prymnesiales, together with "naked" haptophytes
- haploid stage is known as Chryschromulina parkeae
- in cells - endosymbiotic coccoid, nitrogen-fixing cyanobacterium
- typical coastal planktonic organisms

http://www.mikrotax.org/Nannotax3/
Hagino et al., 2013, Plos One

Coccolithophores and global calcification

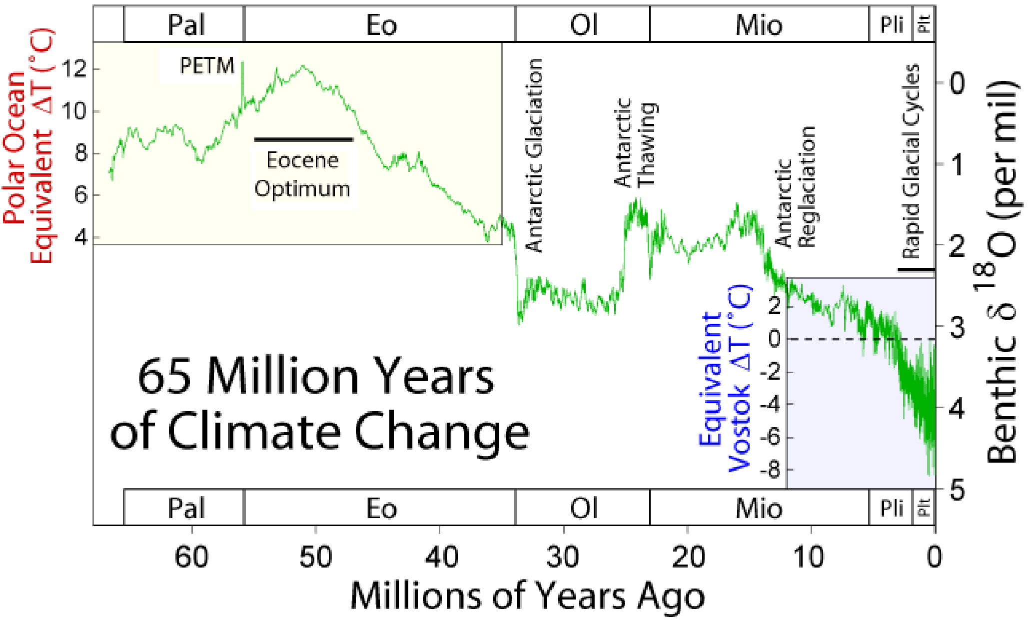


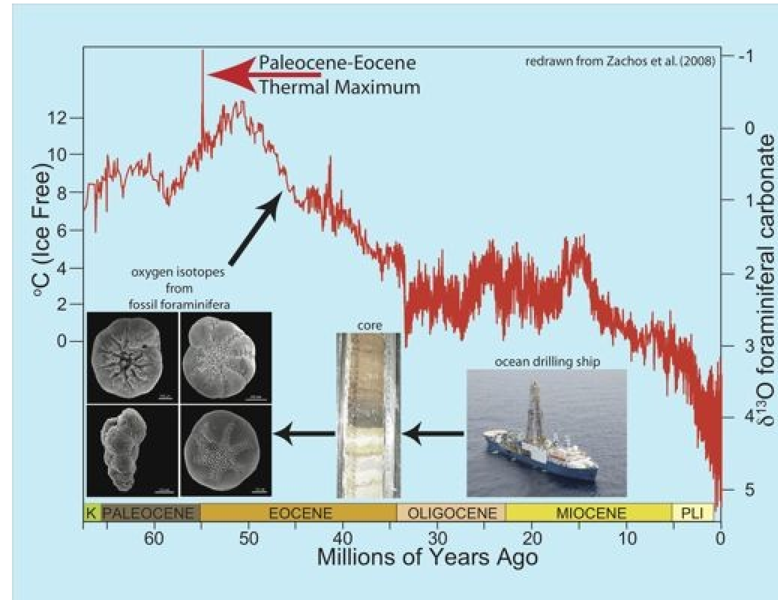


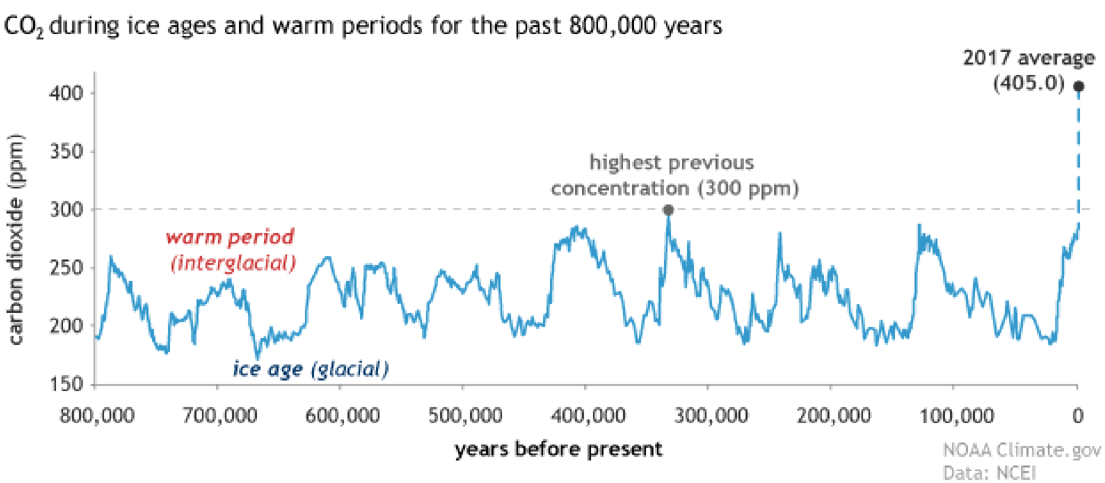


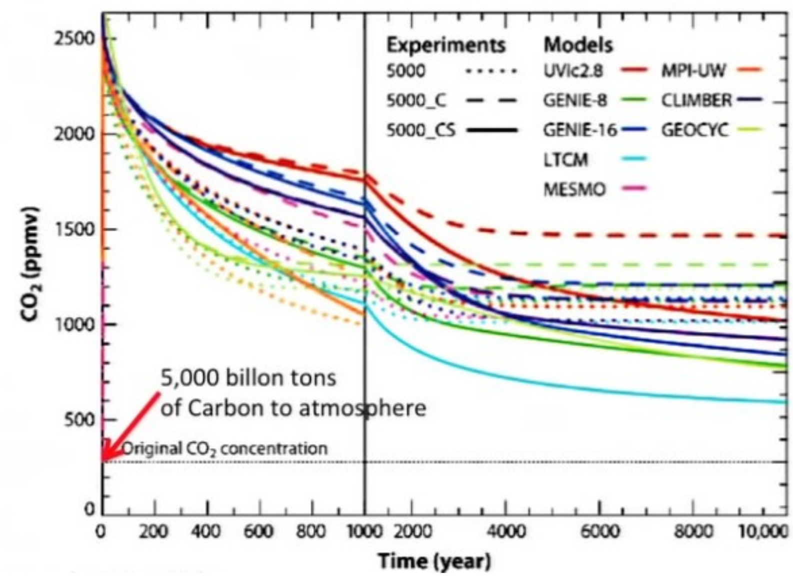
Betzler et al., 2017, IODP; Anderson, 2016, Oceanbites

global climate and the carbon cycle



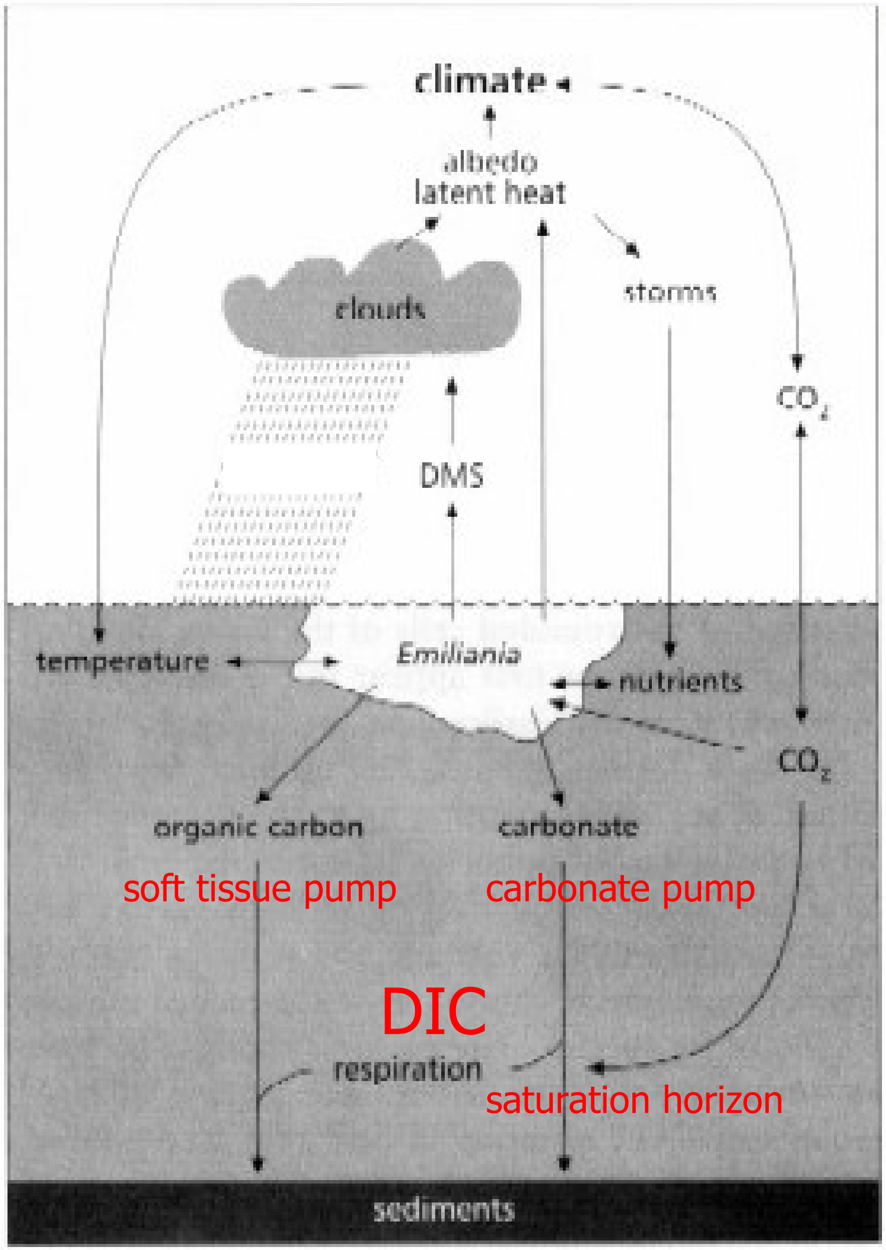


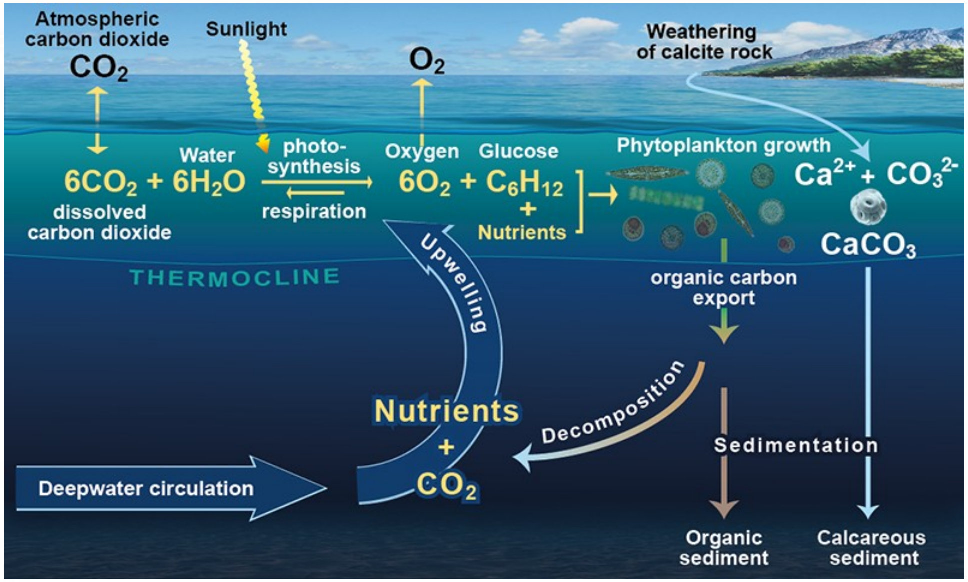




calcifying organisms, such as Coccolithophores, provide long-term carbon sink mechanisms, compensating for instantaneous CO_2 excursions

Archer et al., 2009, AREPS
NOAA Climate.gov





calcification:

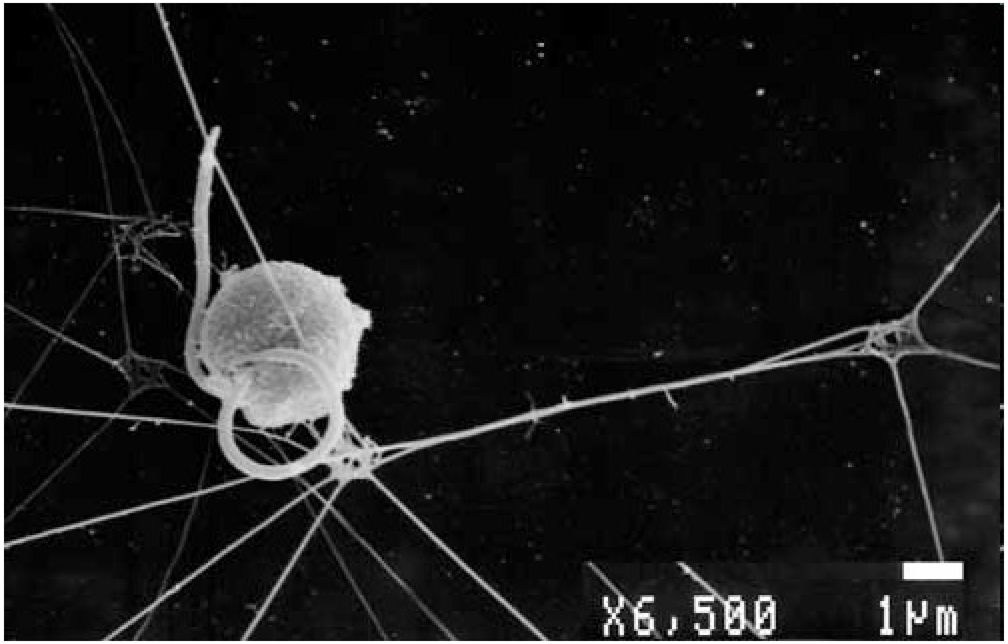
$$2\ HCO_3^- + Ca^{2+} = CaCO_3 + CO_2 + H_2O$$

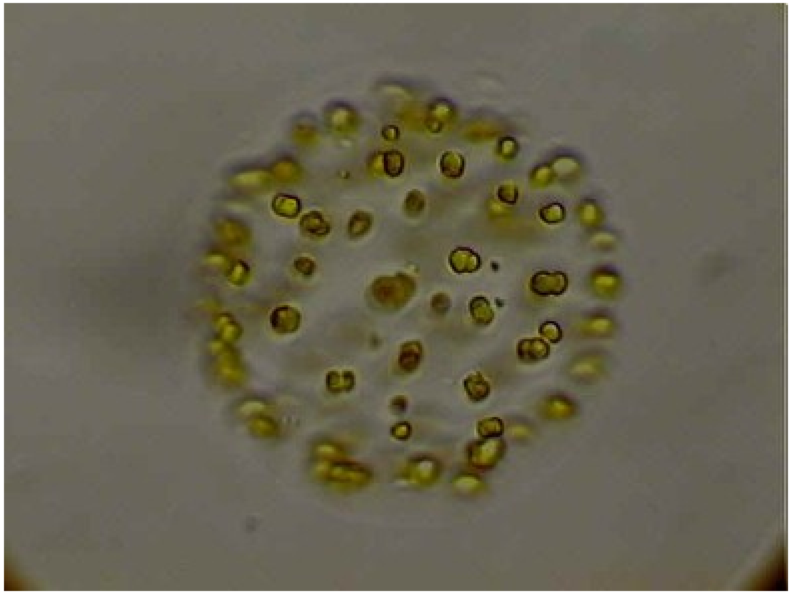
only about 0.5% of $CaCO_3$ produced at the surface reaches the ocean floor

DIC is about 15% higher in ocean depths and this is of key importance for athmospheric CO_2 levels

saturation horizon – below which $CaCO_3$ dissolves

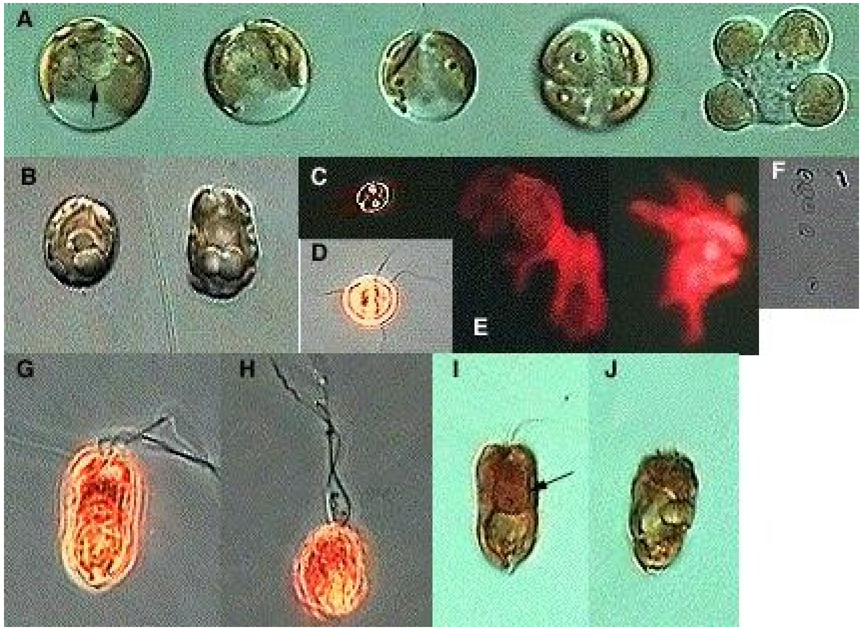
Phaeocystis – flagellate with sticky chitinous filaments



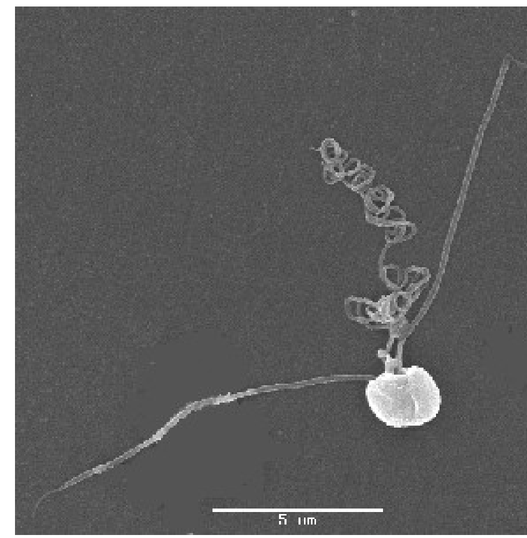


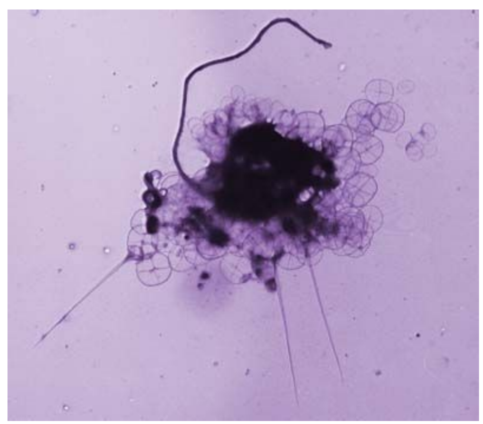
genus *Phaeocystis* - ca 10% of global DMS production, coastal white tides

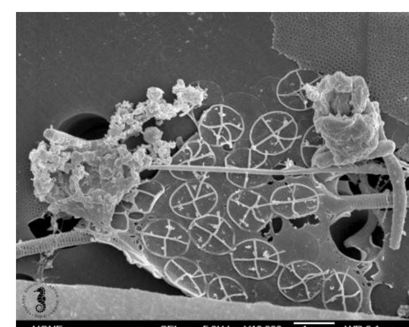
Chrysochromulina



zdroj: nordicmicroalgae.org



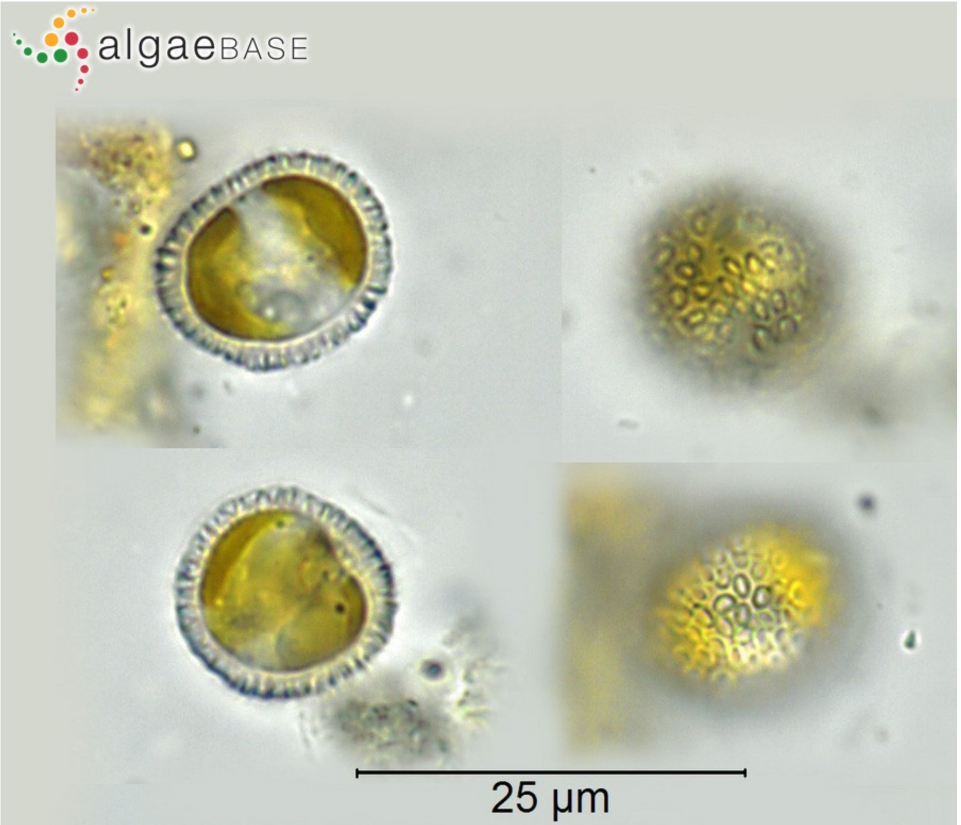


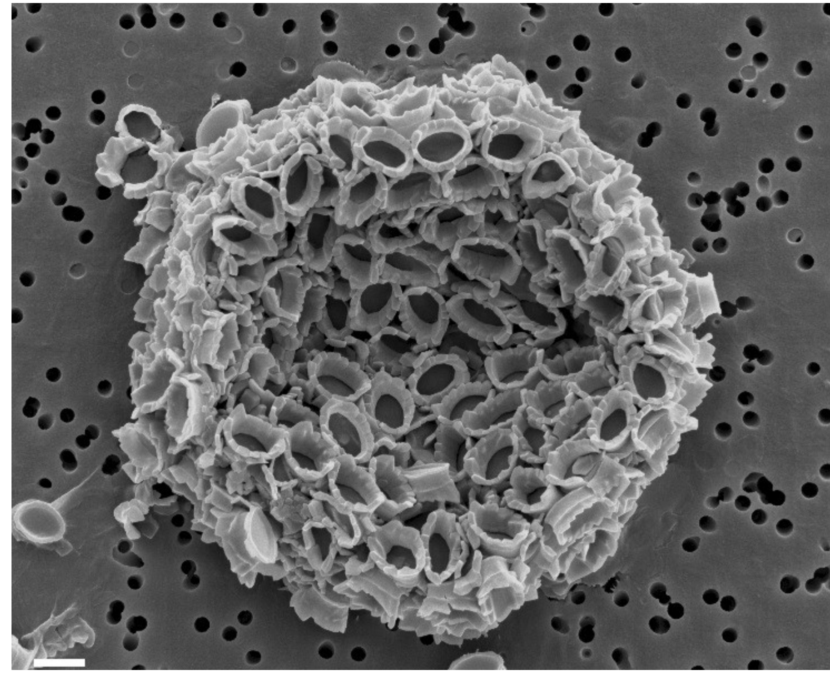


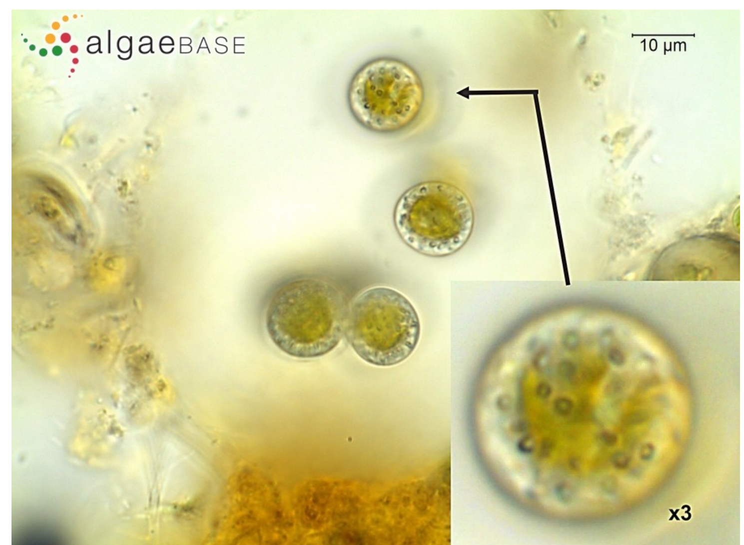
organic scales

unicellular, planktonic marine [rarely freshwater] flagellates
haptonema usually prominent – attachment to the substrate or to the prey
mixotrophy - phagotrophy, osmotrophy

Hymenomonas - a freshwater coccolithophore genus





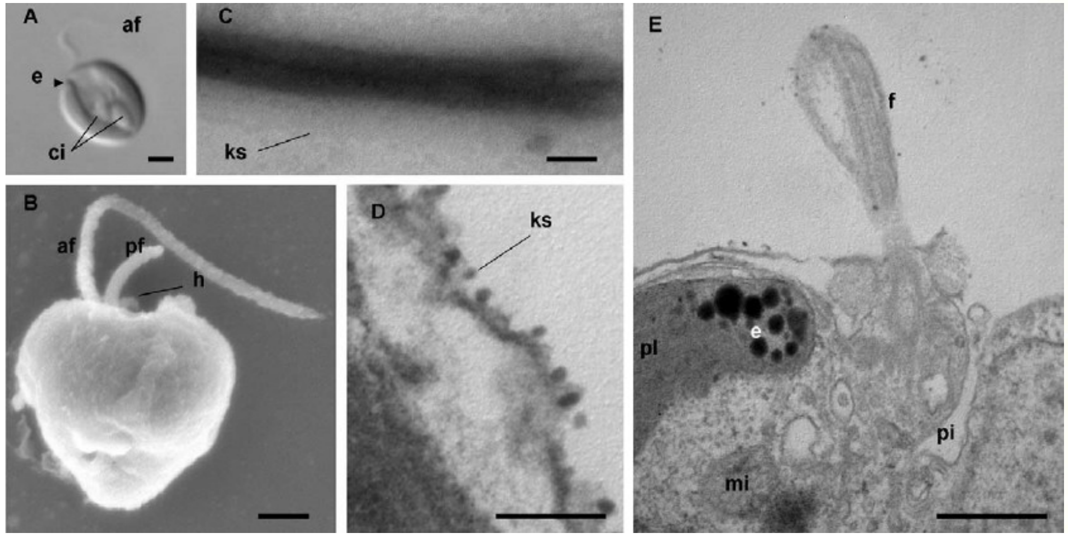


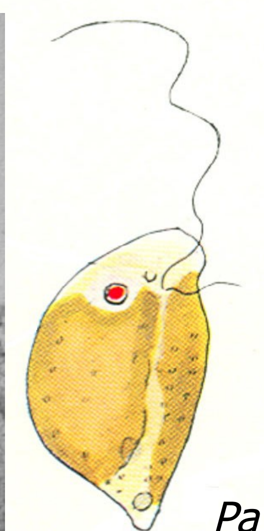
nonmotile haploid cells (*Apistonema* stage) and flagellated diploid stage

occurs in oligotrophic phytoplankton

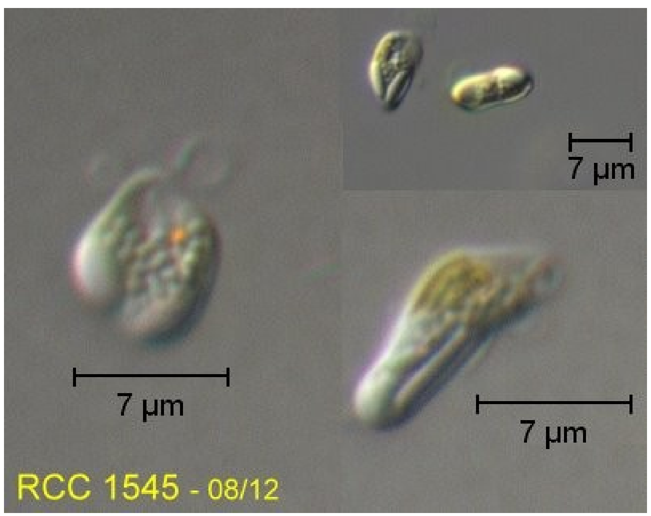
Pavlovophyceae - non-calcified flagellates, incl. some brackish and freshwater taxa

Exanthemachrysis
Pavlova
Rebecca
Diacronema

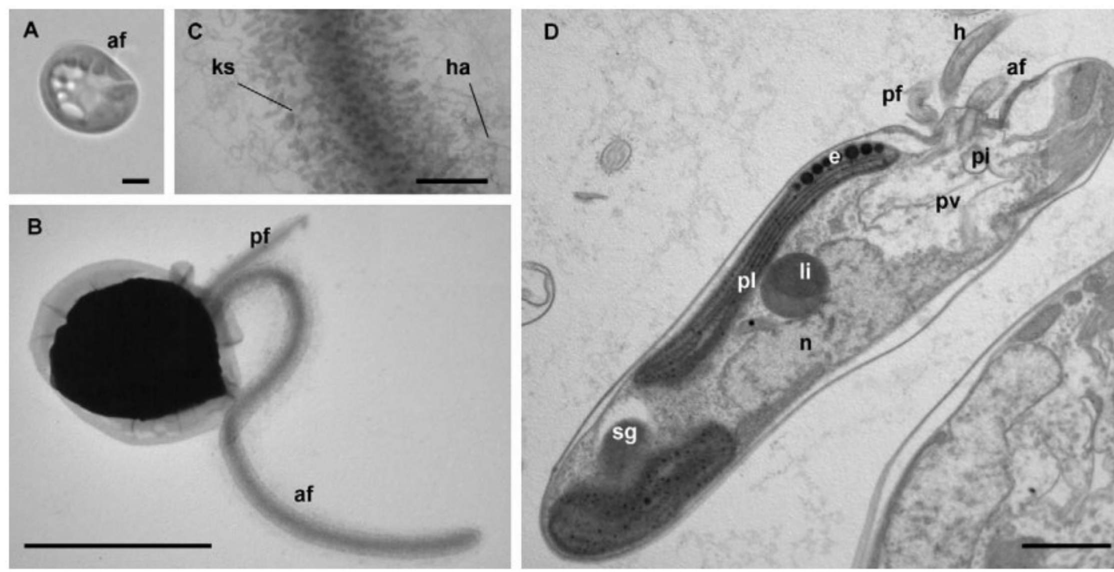




Pavlova



Rebecca salina

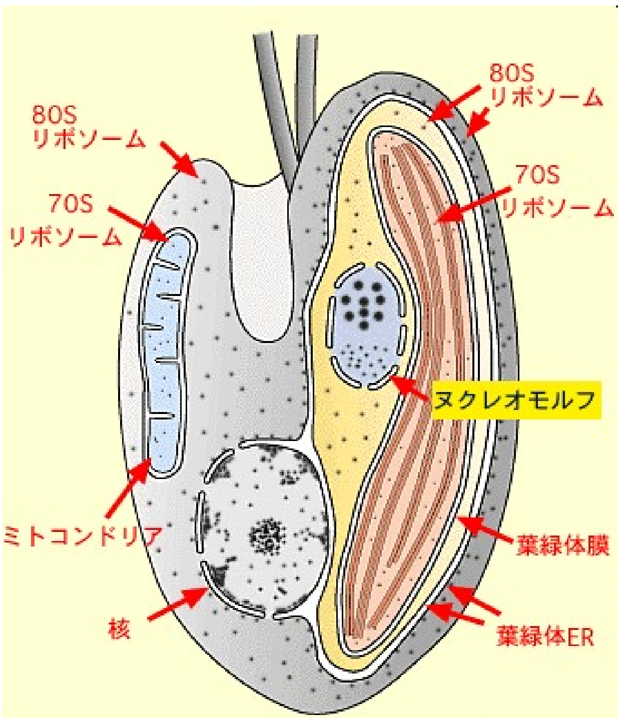


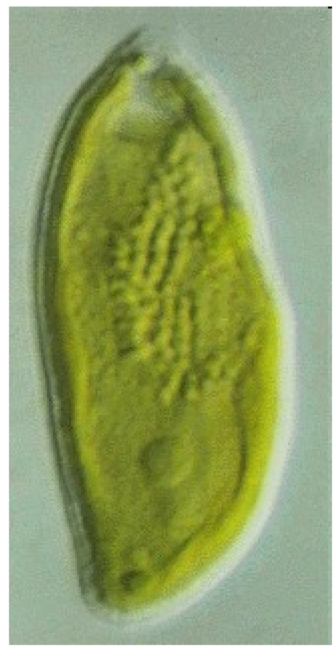
Diacronema (Corcontochrysis) noctivaga

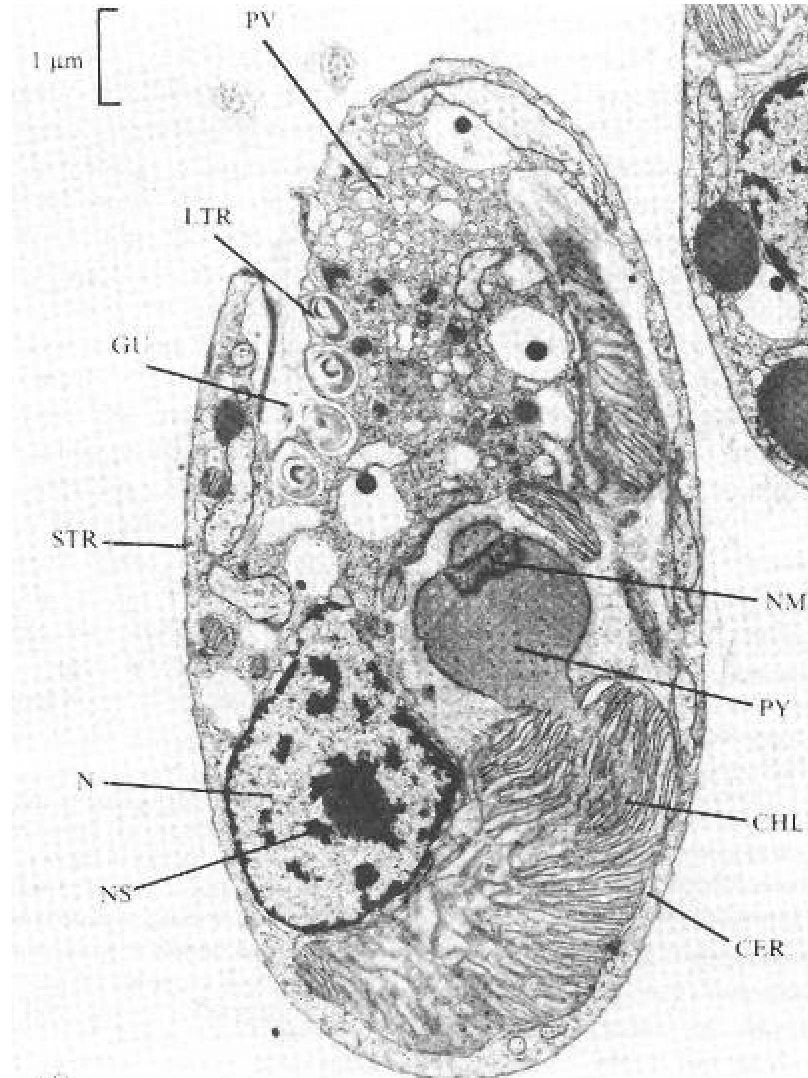
Bendif et al., 2011, Protist

Cryptophyta

cryptophytes – flagellates with (red algal) nucleomorphs,
phycobilins (without phycobilisomes) and trichocysts (heterotrophic nutition)

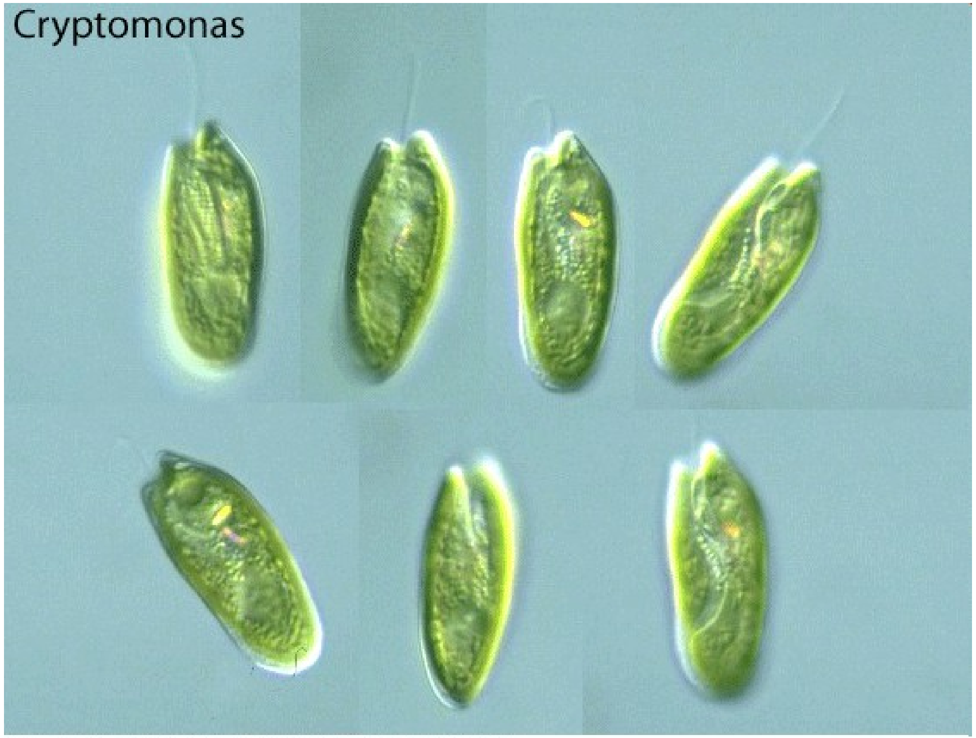






plankton of freshwater and seas, about 200 species

Cryptomonas – most frequent freshwater genus



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marine cryptophytes – e.g. *Rhodomonas* a *Chroomonas*
mostly (sub-)tropical shelf seas