

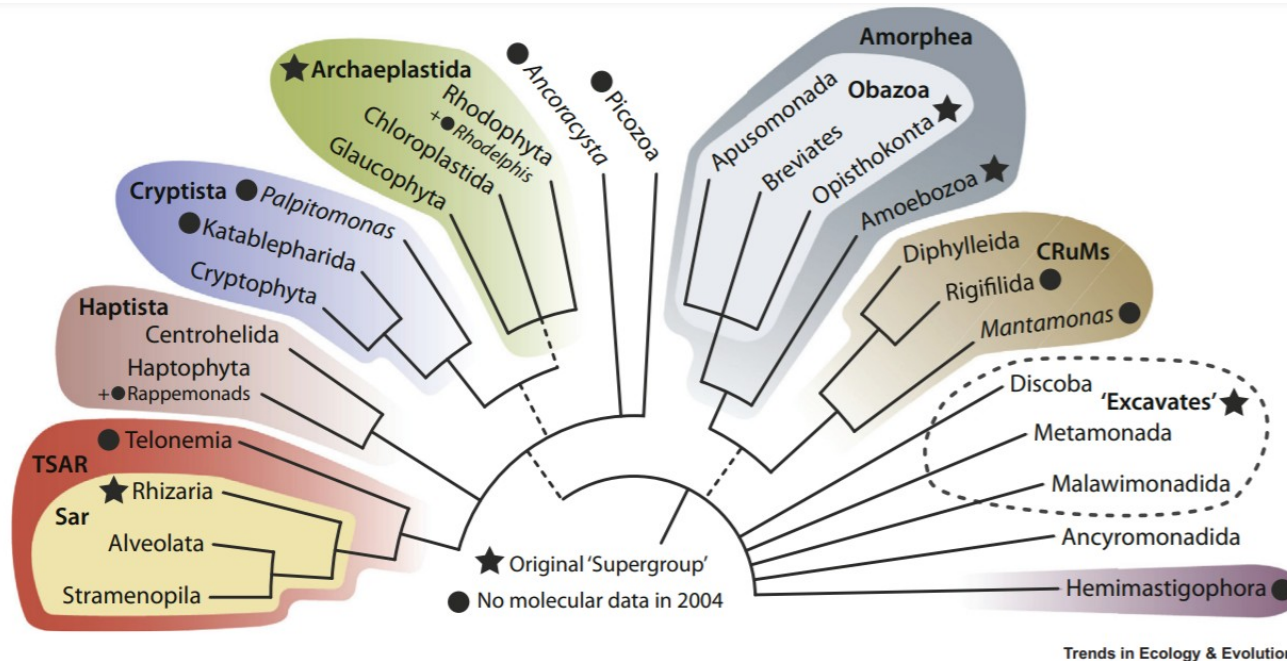
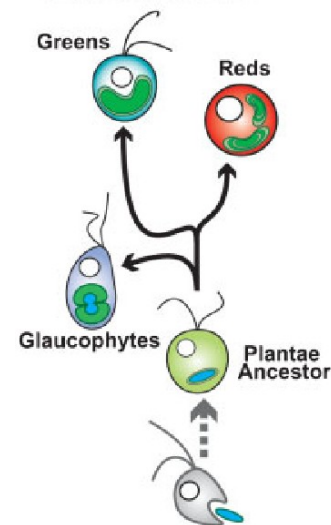


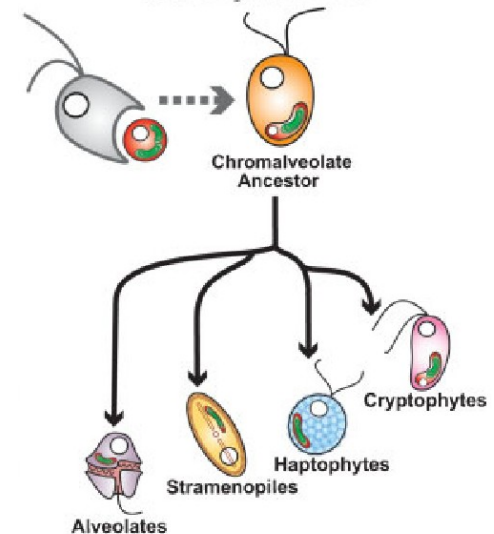
**Figure 1. The New Tree of Eukaryotes.**

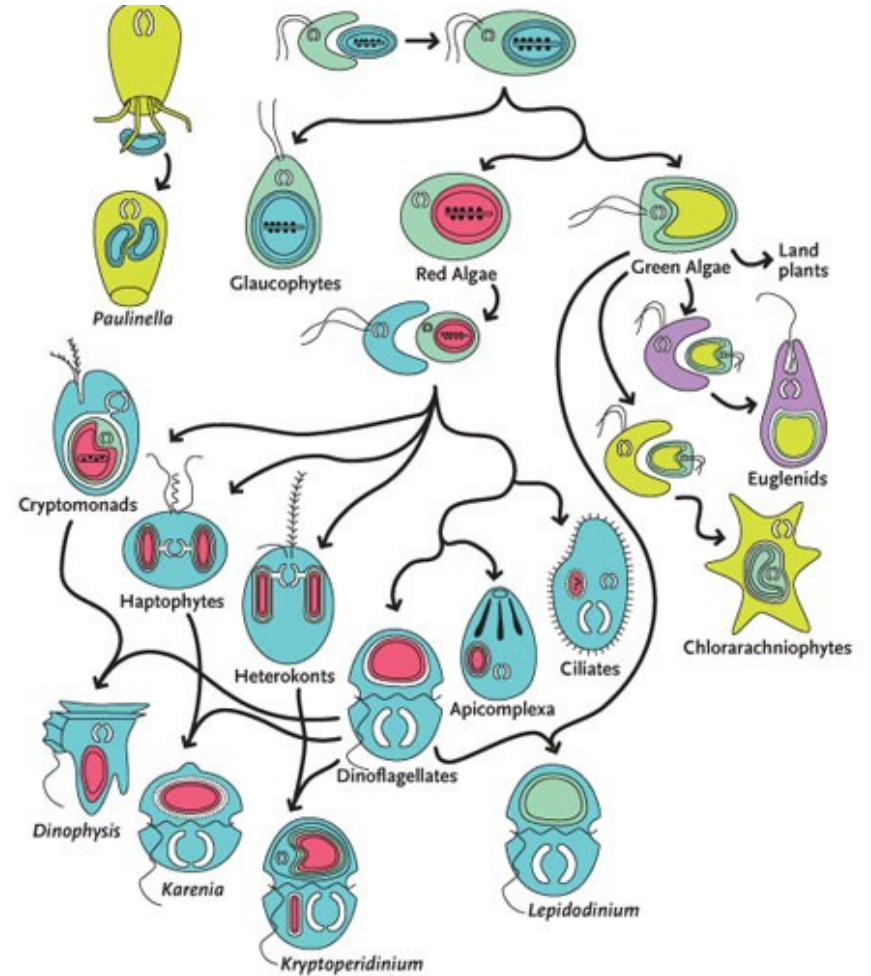
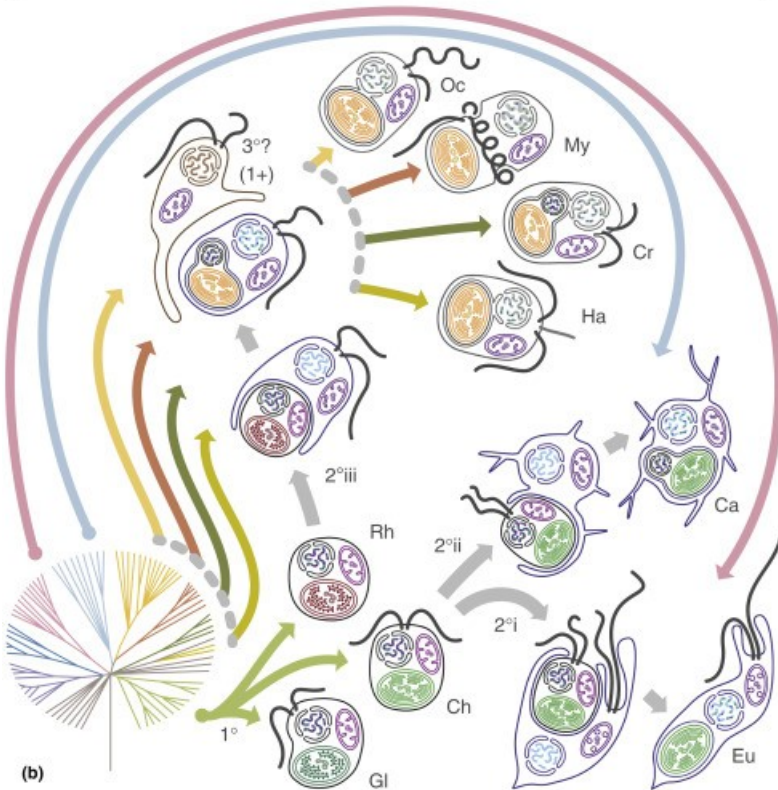
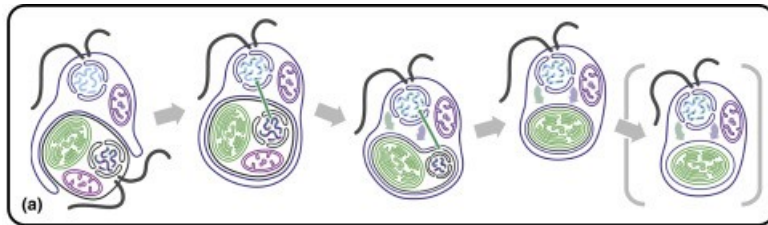
This summary is based on a consensus of recent phylogenomic studies. The colored groupings correspond to the current 'supergroups'. Unresolved branching orders among lineages are shown as multifurcations. Broken lines reflect lesser uncertainties about the monophyly of certain groups. Star symbols denote 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).

## Primary Endosymbiosis



## Secondary Endosymbiosis



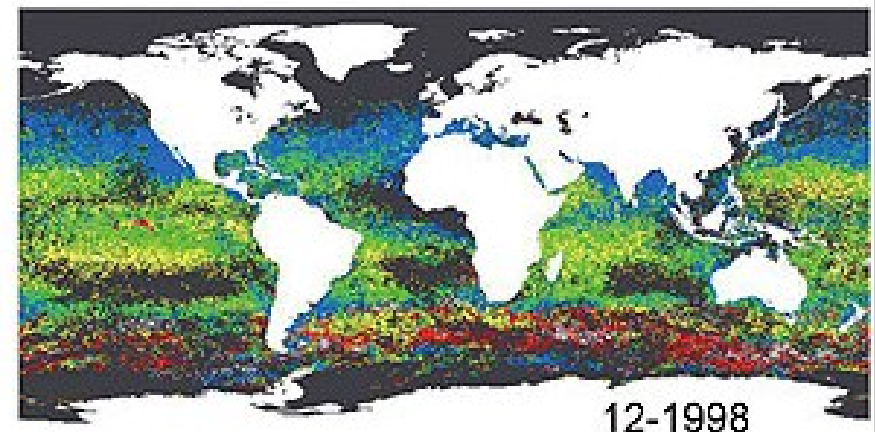
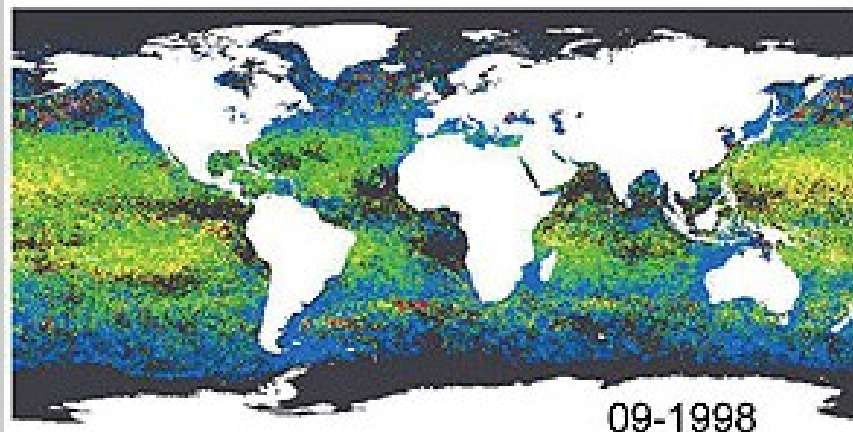
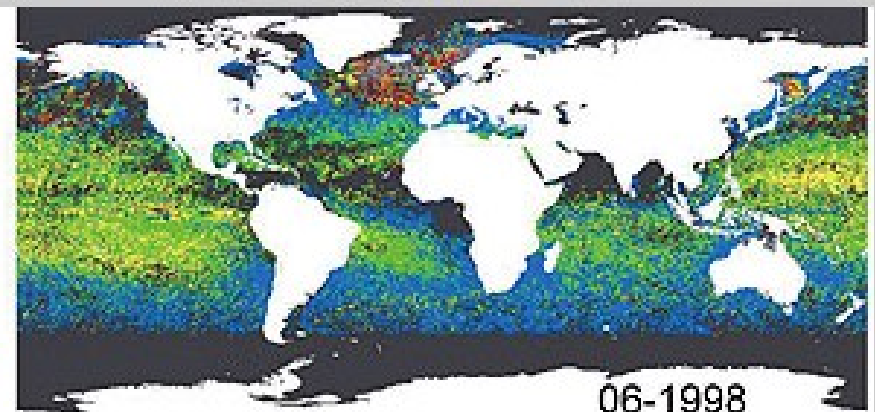
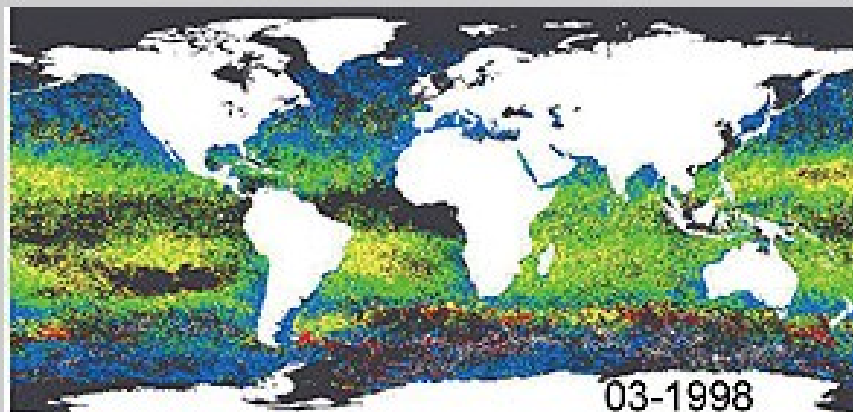


[very simplified] schemes of plastid endosymbioses

(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.



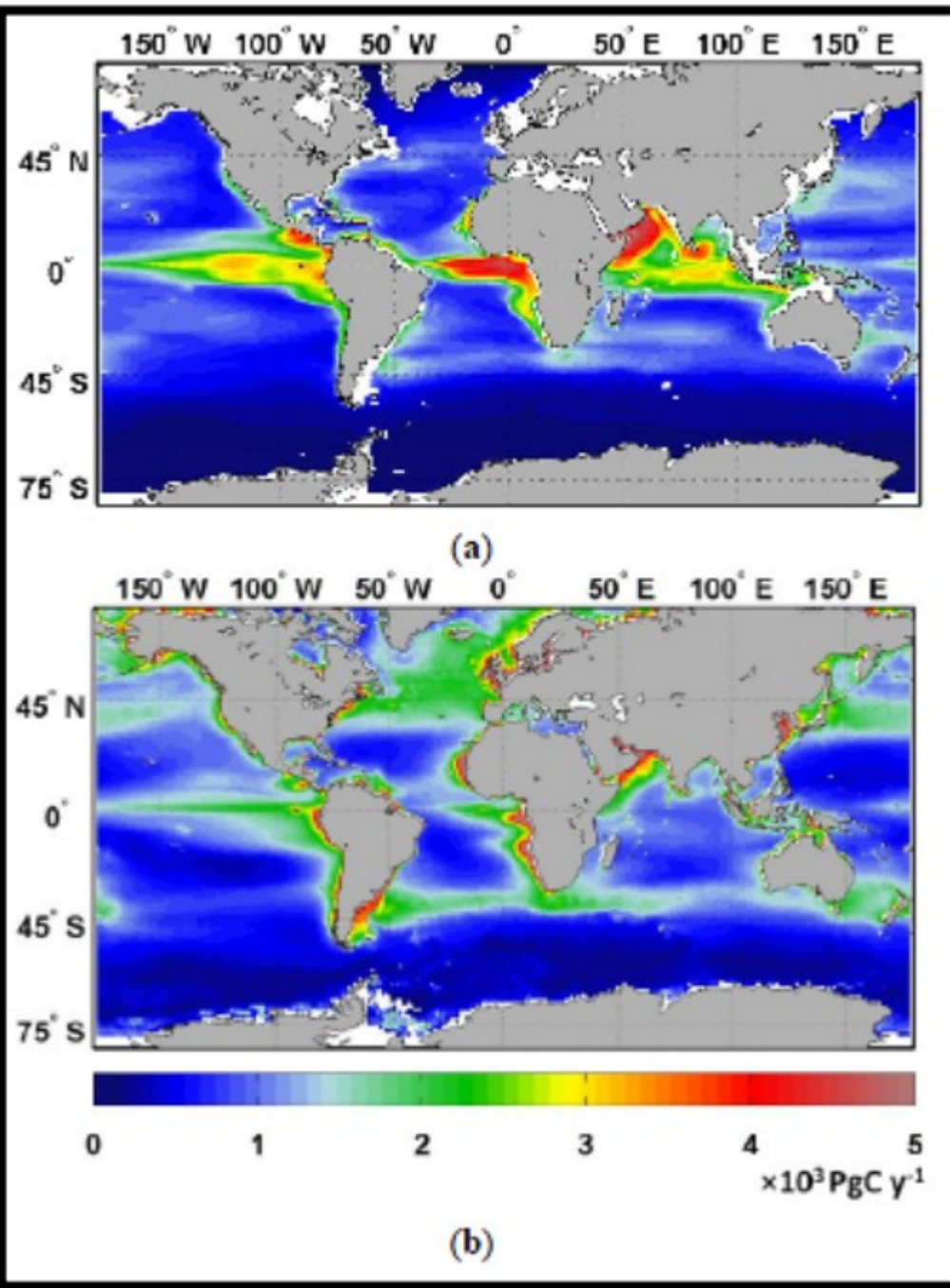
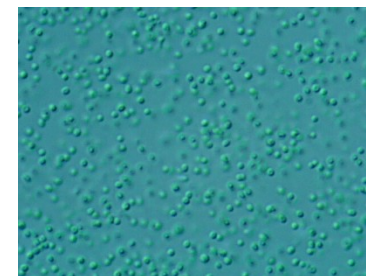
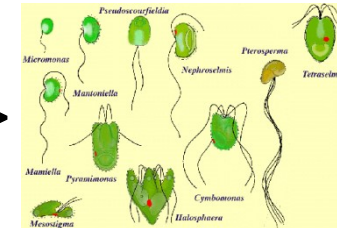


Figure 1. Climatological map Distribution of annual marine NPP for (a) NASA Ocean Biogeochemical Model and (b) Vertically-Integrated Production Model (VGPM) for the period from September 1998 to 2011 (Rousseaux – August 1999 (Blue < 100 g C m<sup>-2</sup>, Green > 110 g C m<sup>-2</sup> and < 400 g C m<sup>-2</sup>, Red > 400 g C m<sup>-2</sup>) (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; Maraňón et al., 2003; Muller-Karger et al., 2005).

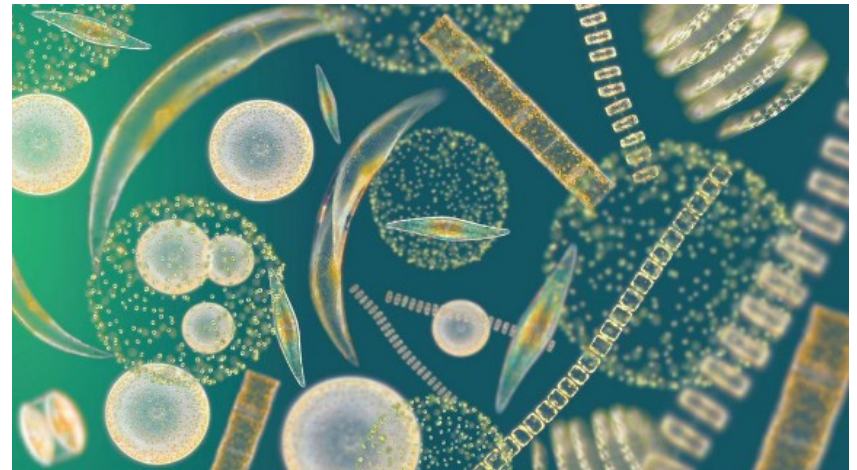
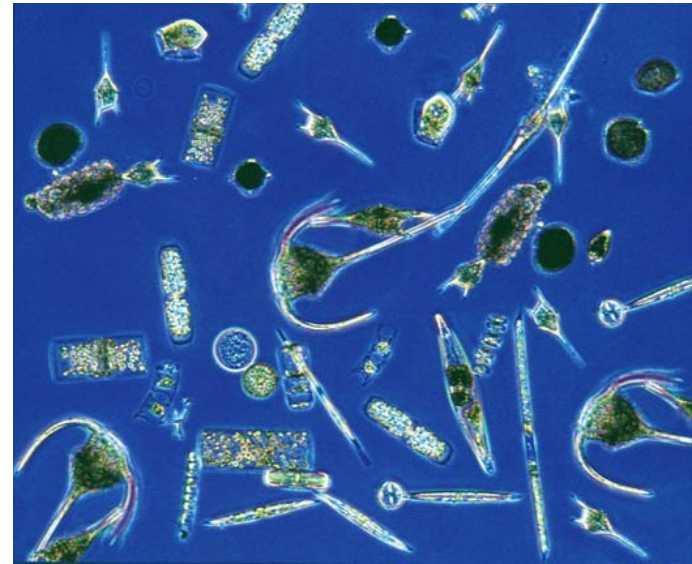
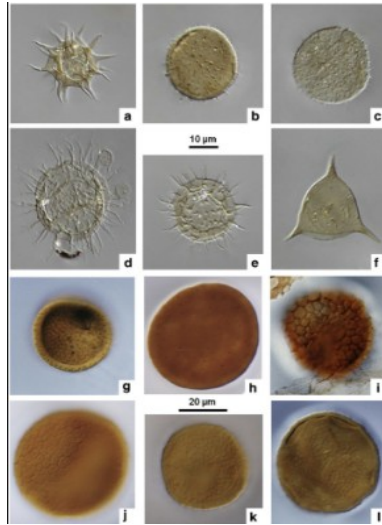


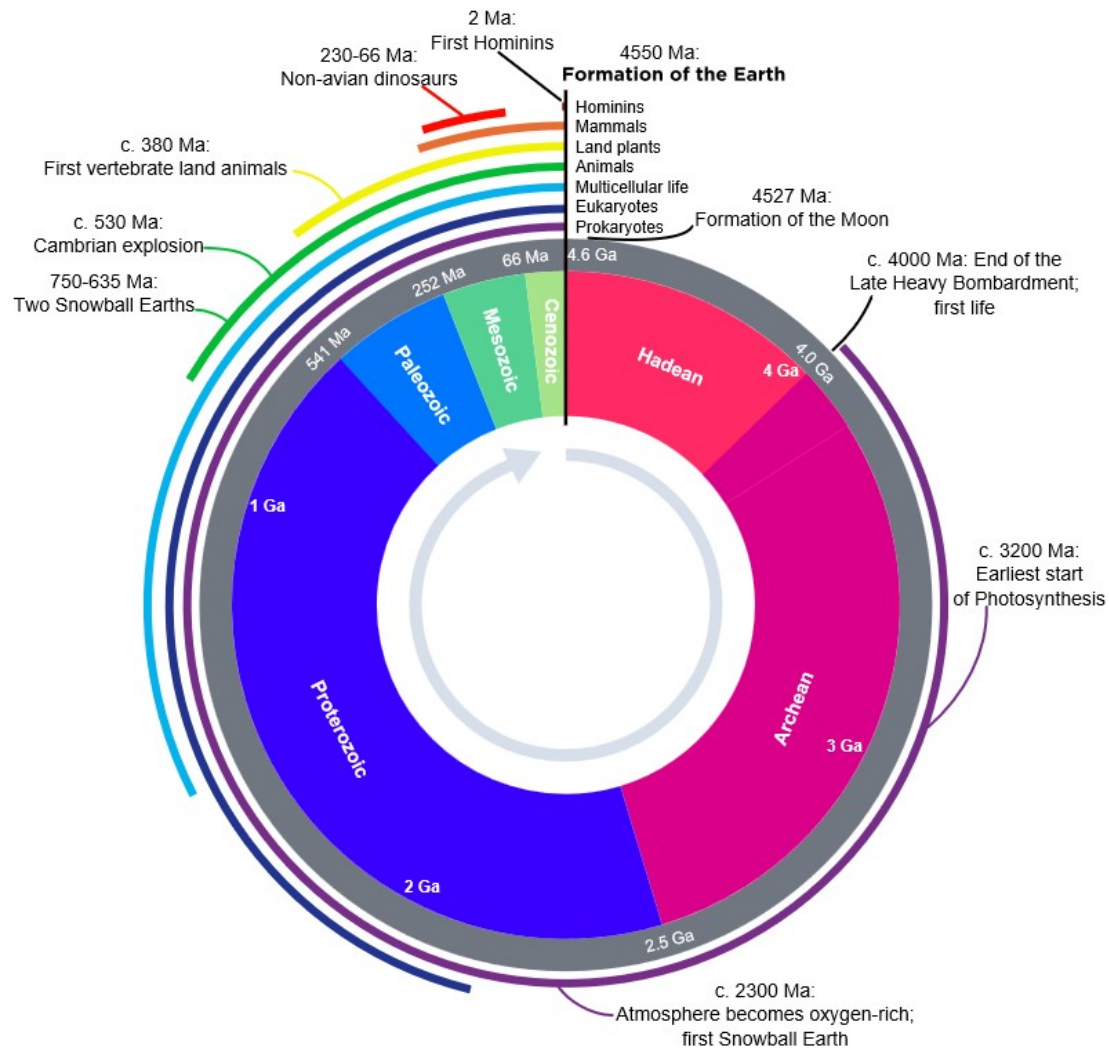
**lineages with secondary  
rhodoplasts in marine  
phytoplankton**

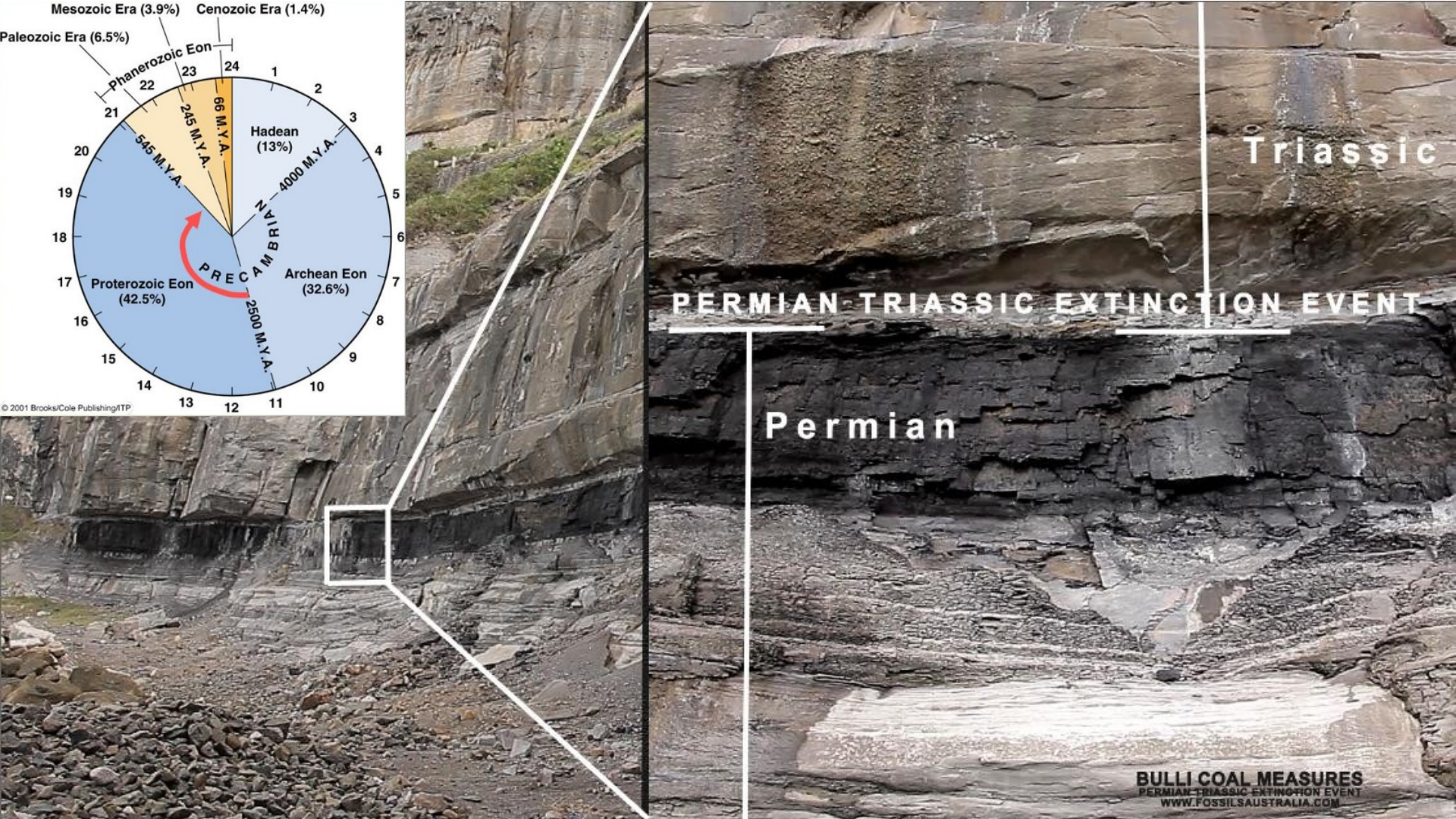
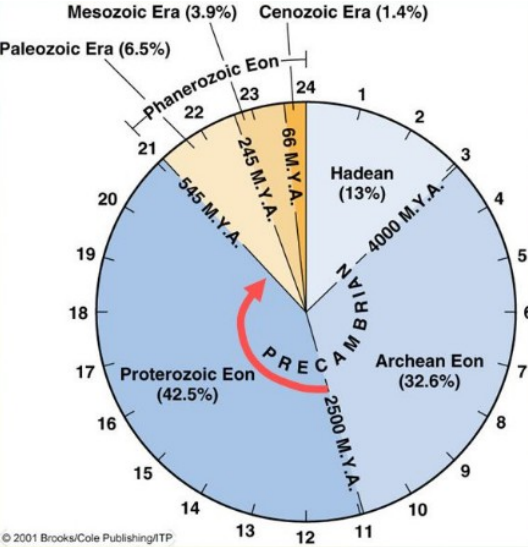
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# palaeozoic vs. recent marine phytoplankton





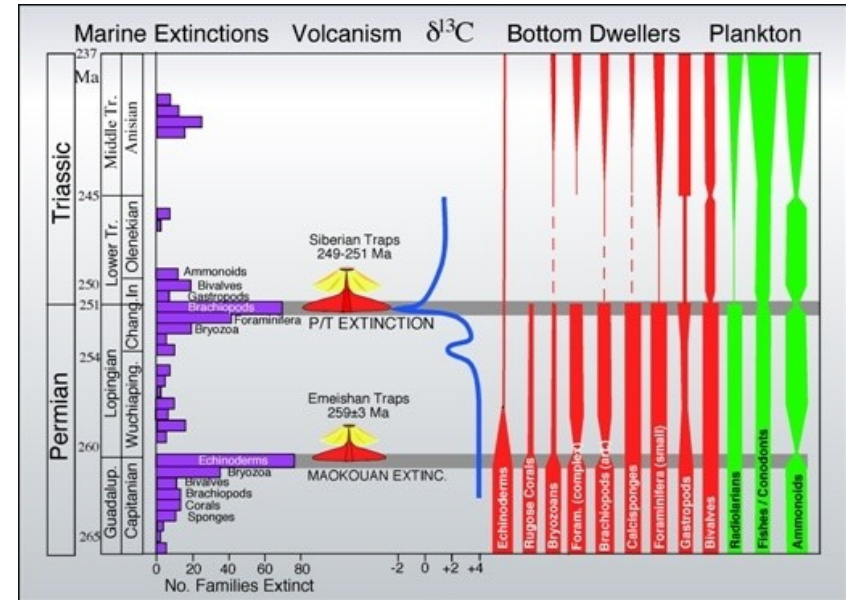


## classical geological boundary Proterozoikum vs. Mesozoikum

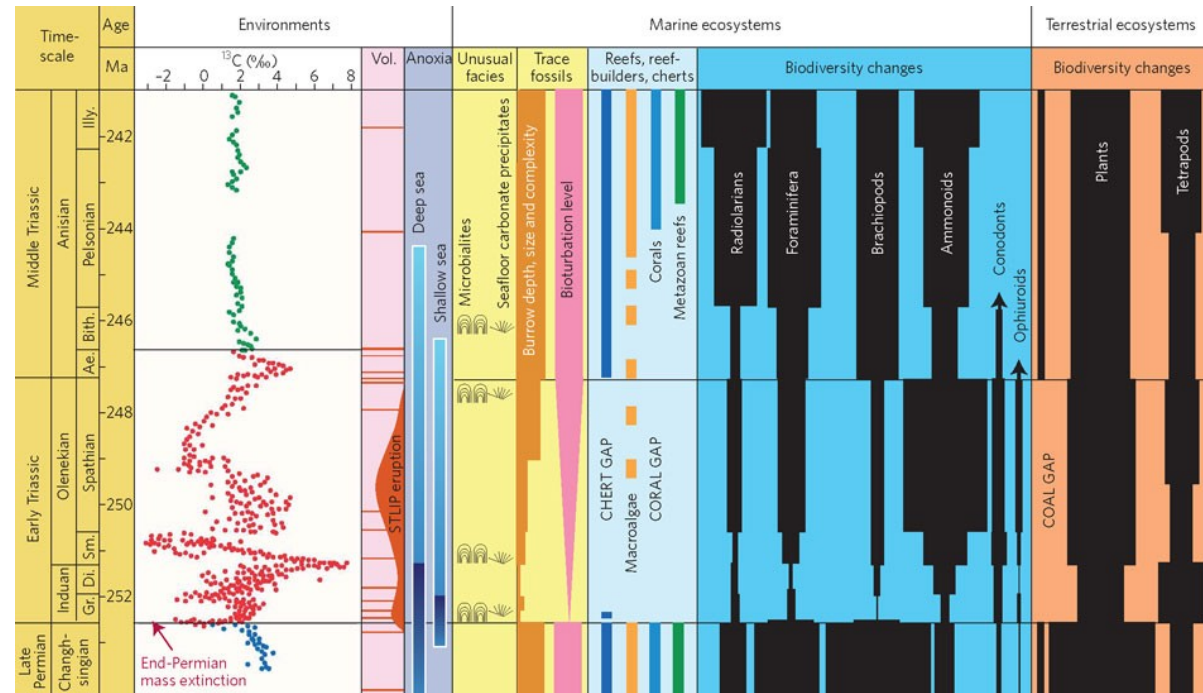
- dramatic decline of diversity (oceans > continents)
- extinction of multiple high-order lineages – including apparent algal/protist groups
- dramatic fluctuation in sea level
- fluctuations in global temperature
- jumps in primary productivity (ratio of C12/C13)
- changes in basic features of rivers (braided vs. meandering)
- long-term change in vegetation patterns
- acidification of oceans and strong increase in their oxygen limitation / anoxia
- increase in atmospheric CO<sub>2</sub>, decline in oxygen concentration

recent estimates of time scale: between  $251.941 \pm 0.037$  and  $251.880 \pm 0.031$  My

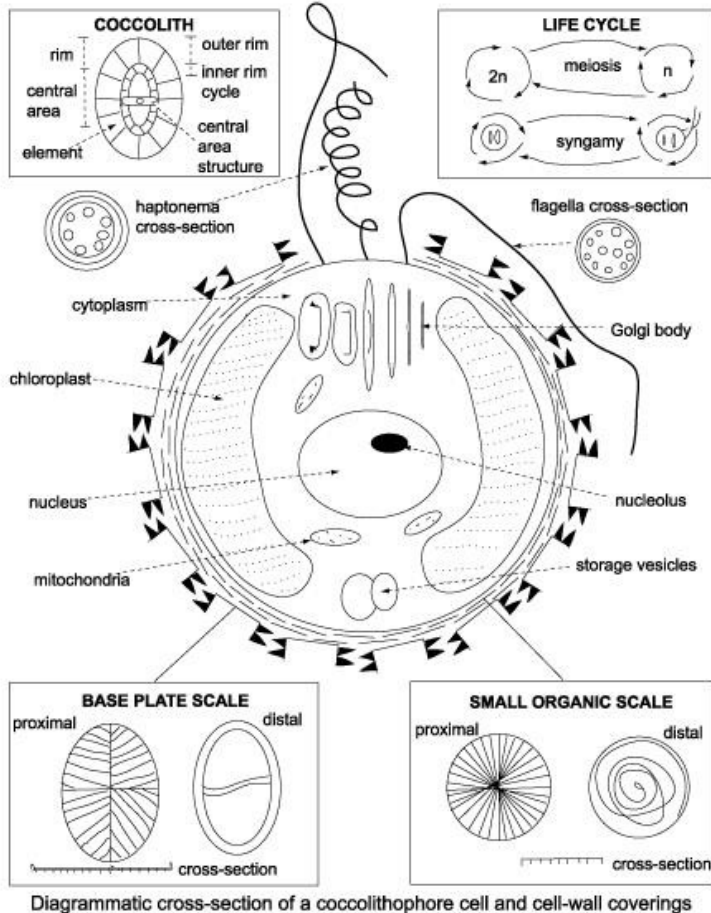
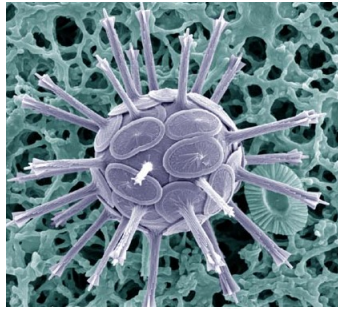
Burges, 2014, Nature 111



Siberian traps



# Haptophyta (Haptista)



haptoneema

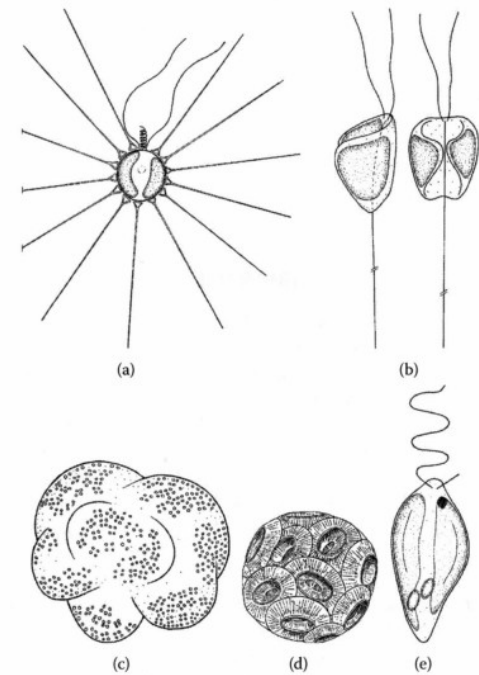
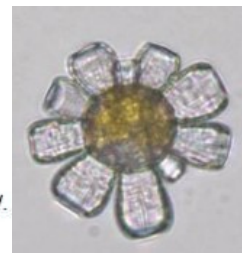


FIGURE 10.1 Haptophytes: (a) *Chrysochromulina hirta*, (b) *Chrysochromulina alifera*, (c) *Phaeocystis pouchetii* colony, (d) *Coccolithus pelagicus*, and (e) *Pavlova gyrams*. (From Throndsen, J., Hasle, G.R., and Tangen, K., *Norsk kystplanktonflora*, Almatr Forlag AS, Oslo, 2003. With permission.)

neage including organisms with key effects on global cosystem (carbon cycle, dimethylsulfide);

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

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

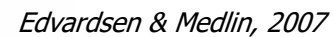


*Scyphosphaera*  
(biomarks.eu)

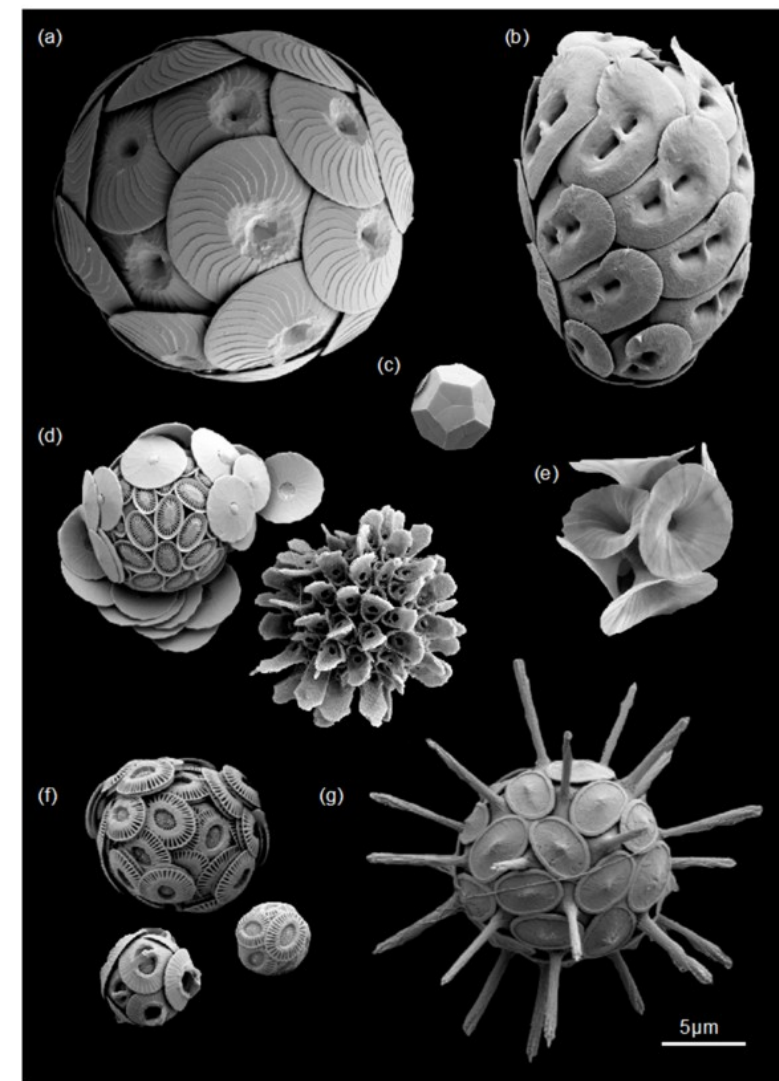
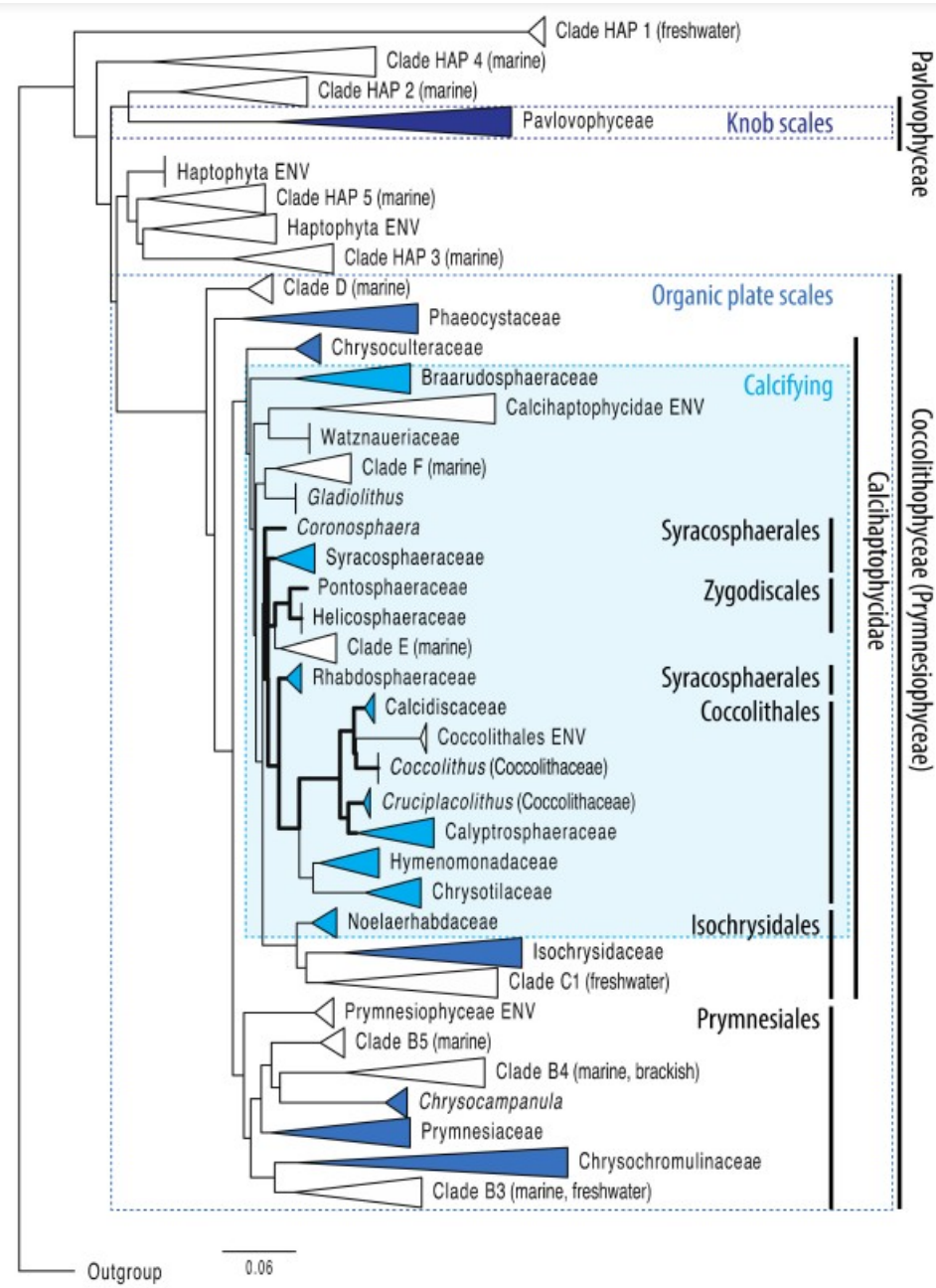
Edvardsen & Medlin, 2007

two classes:  
Pavlovophyceae  
Coccolithophyceae

Pavlovophyceae  
Coccolithophyceae



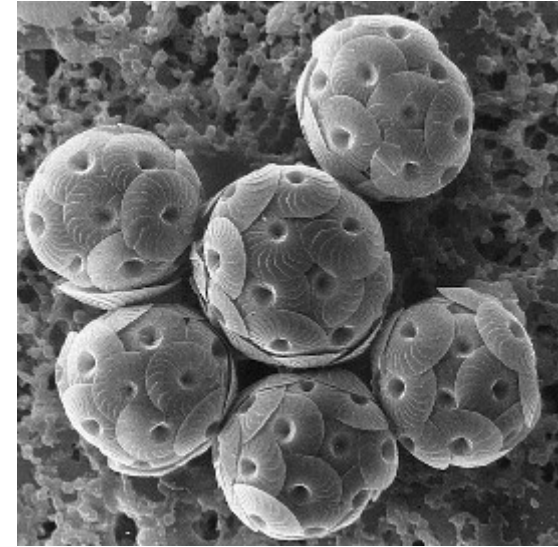
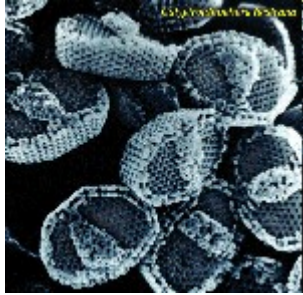
# Haptophyta – phylogeny and systematics



# *Coccolithophyceae*

coccoliths – calcium carbonate scales on cellular surface

holococcoliths – develop externally on cells



heterococcoliths – develop inside the cells, complex 3D shapes



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

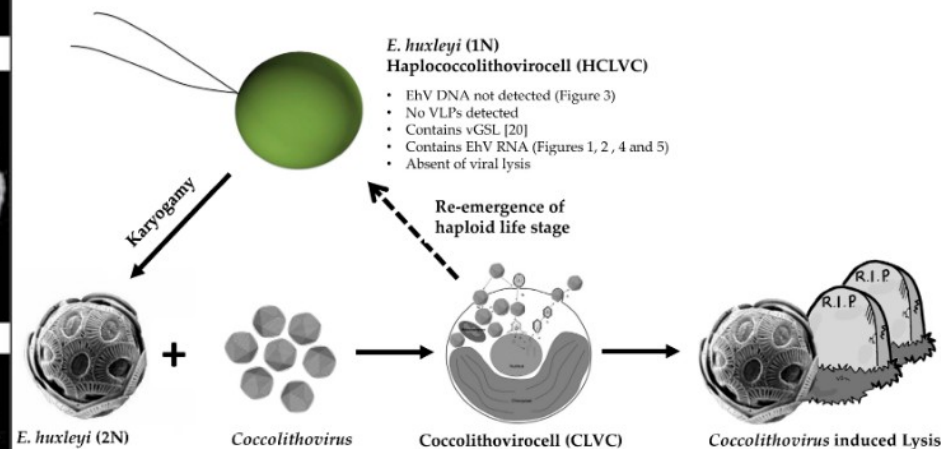
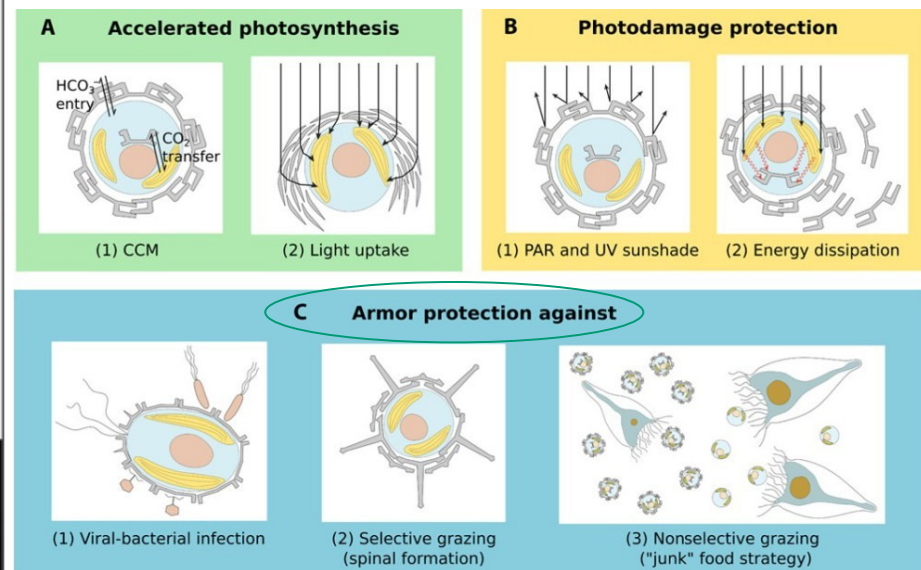
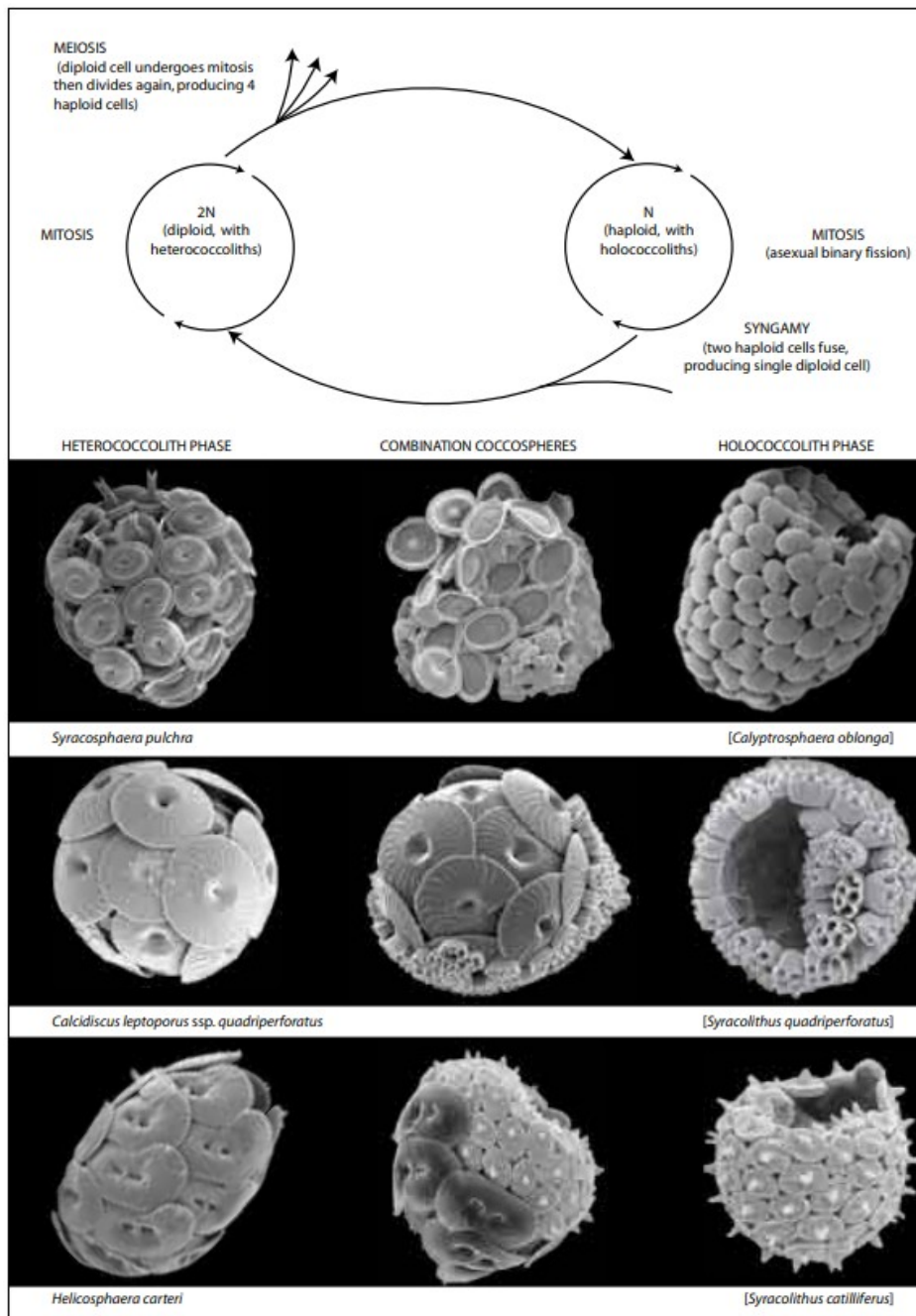
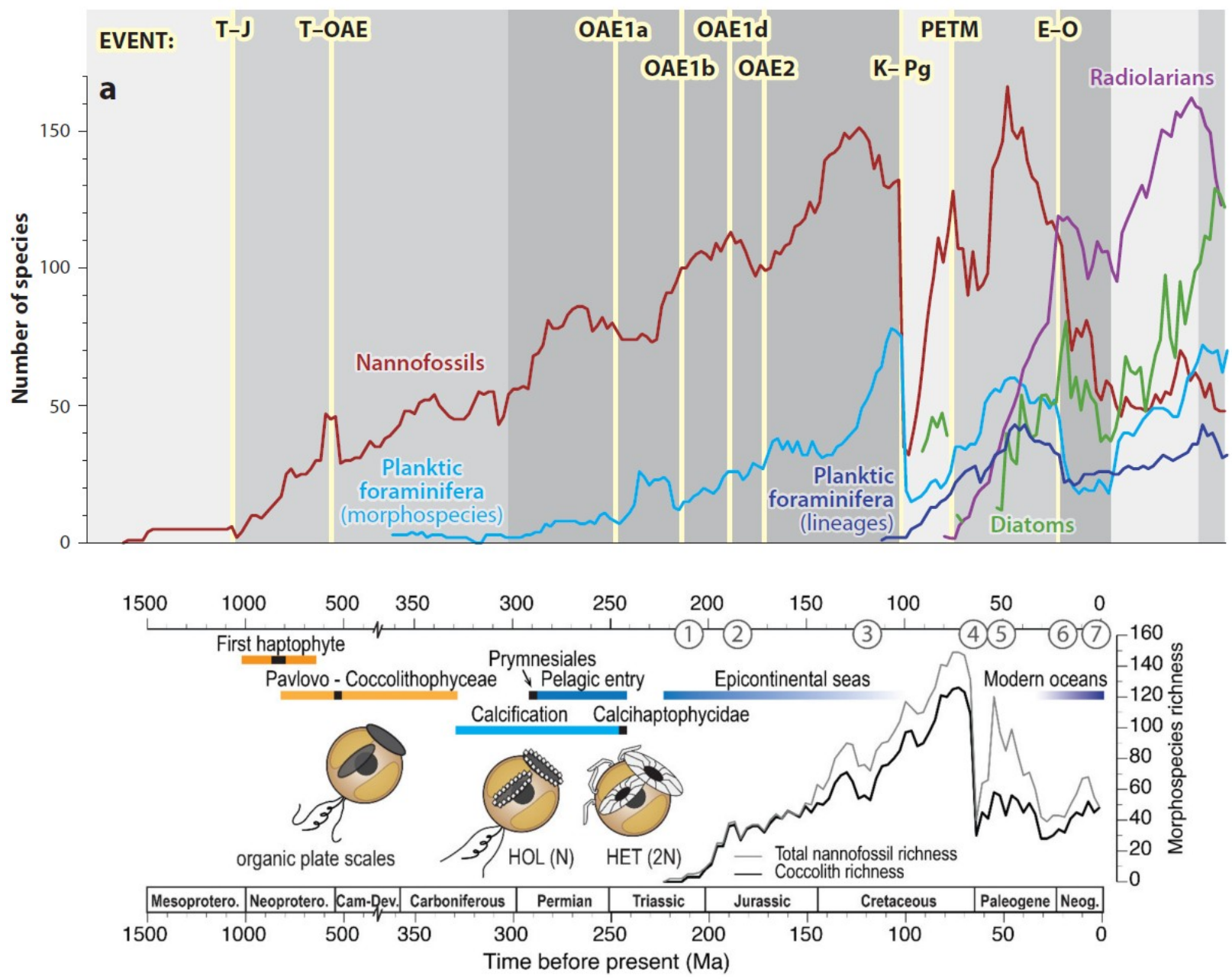


Figure 2 - Typical coccolithophore life-cycle, and three examples

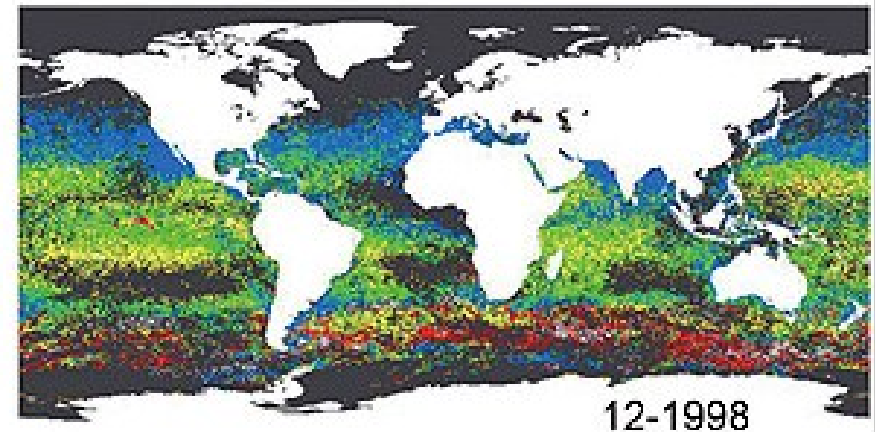
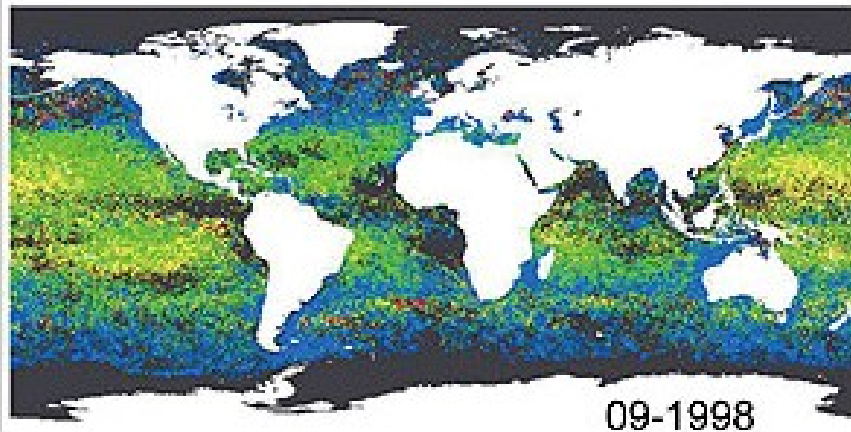
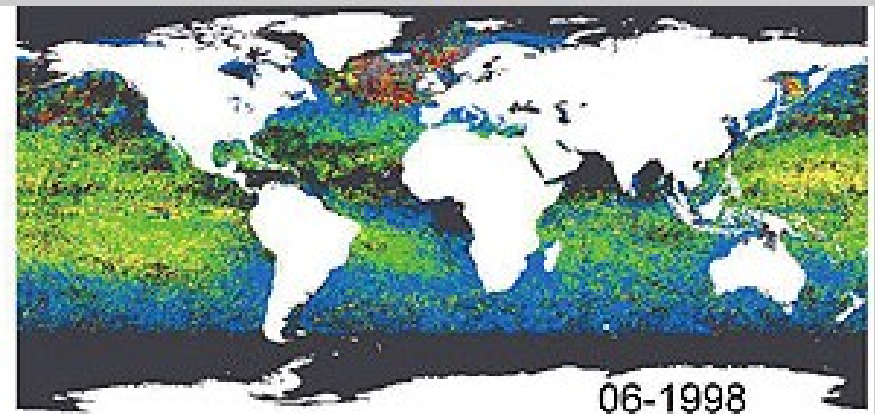
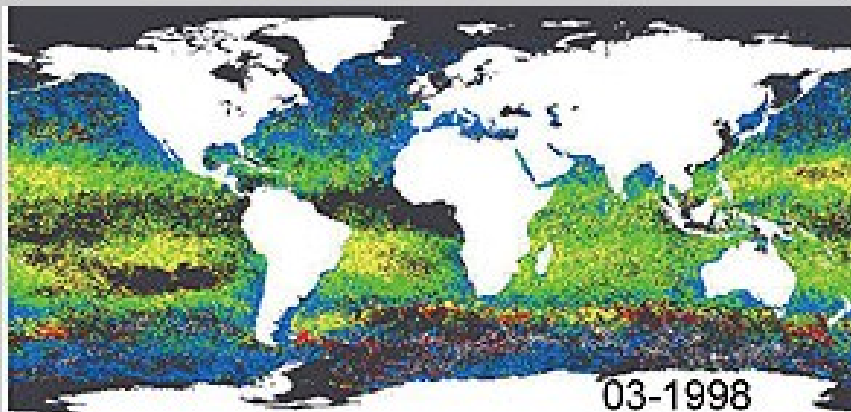
Young et al., 2003, *Journal of Nannoplankton Research*  
 Mordecai et al., 2017, *Viruses*  
 Anderson, 2016, *Oceanbites*

# Evolutionary patterns of diversity in major marine phytoplankton groups



## 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* dominant en permanence dans les régions tropicales.



survival ages of haptophyte taxa

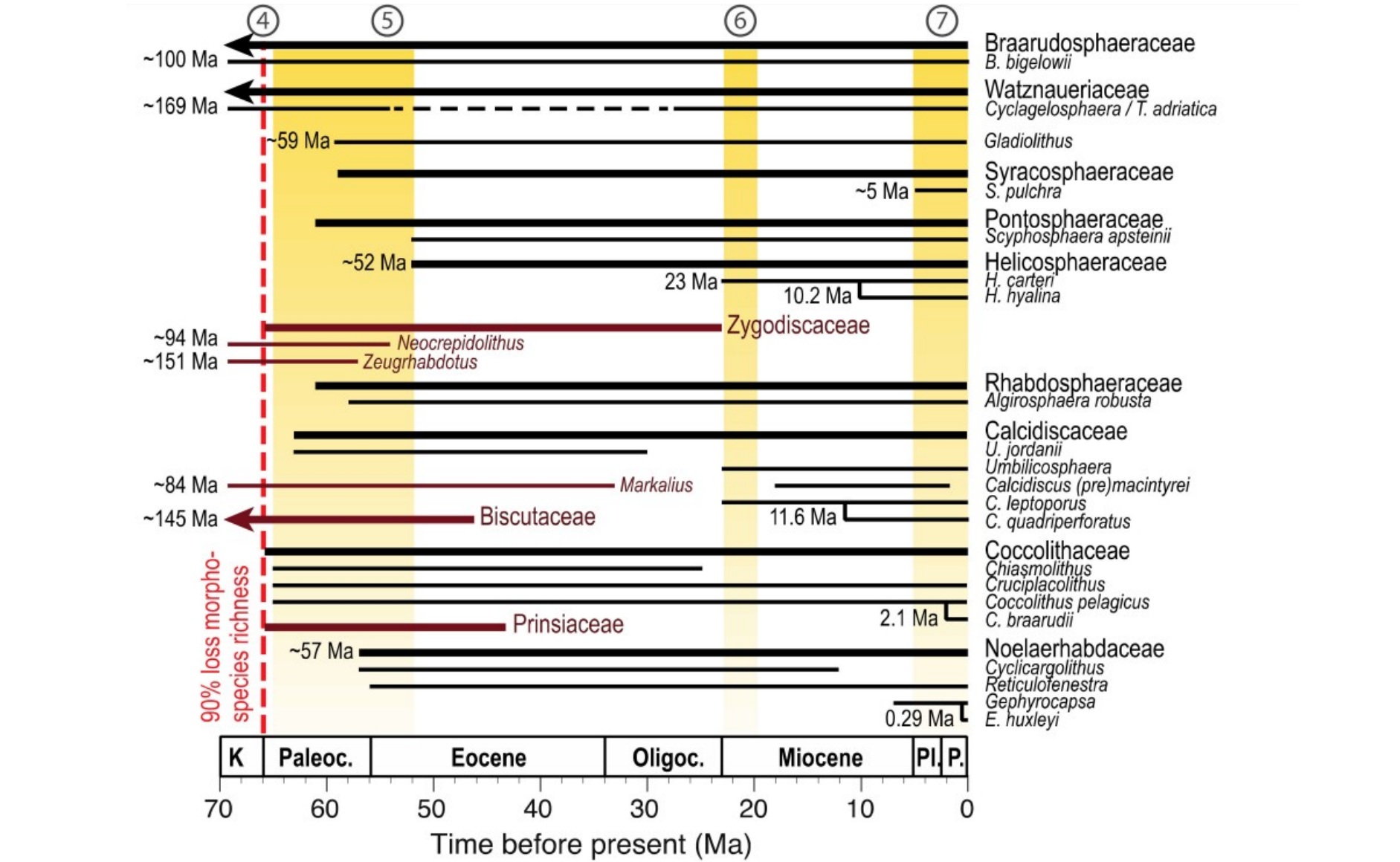
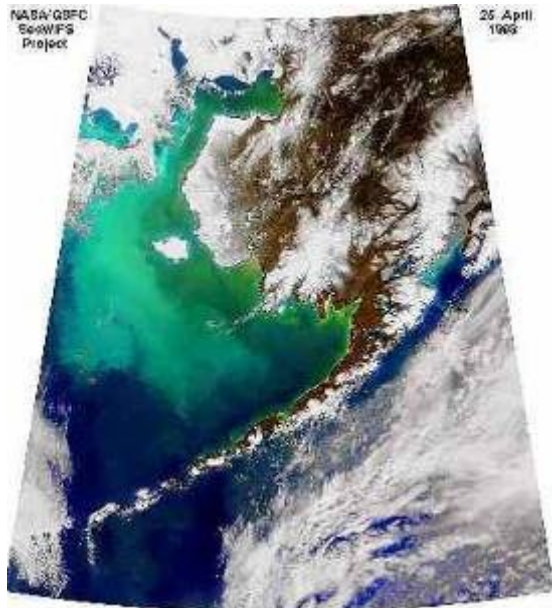
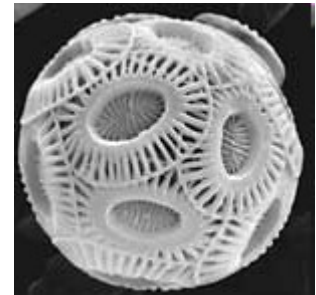


**Figure 5.** Fossil ranges of key modern coccolithophore clades. Few lineages with Mesozoic origins survived the K-Pg mass extinction event at ~66 Ma (red dashed line) and continued into the Cenozoic era,

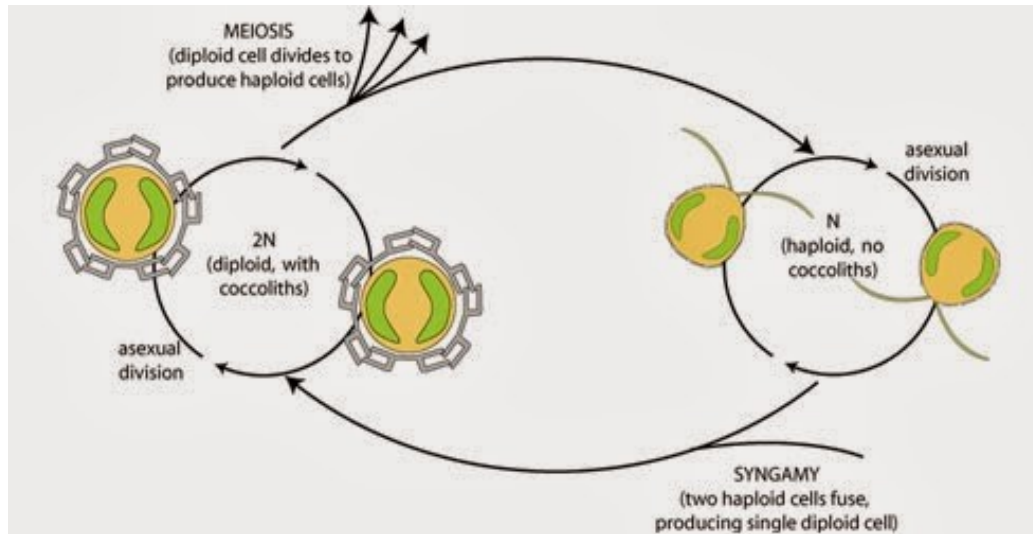
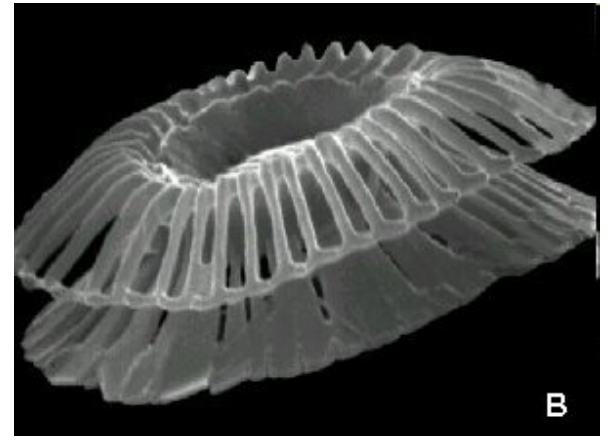
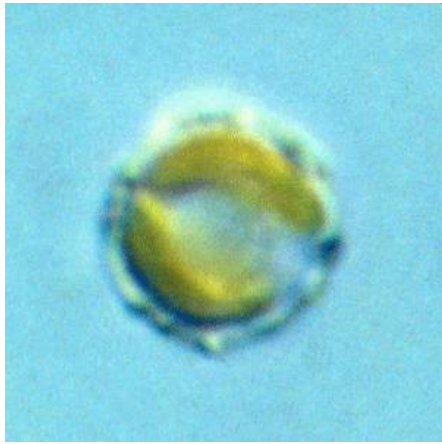
white tides



and - dimethylsulfide -  
source for the  
condensation nuclei of  
clouds



*Gephyrocapsa huxleyi* – one of the most frequent recently occurring eukaryotes on Earth



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

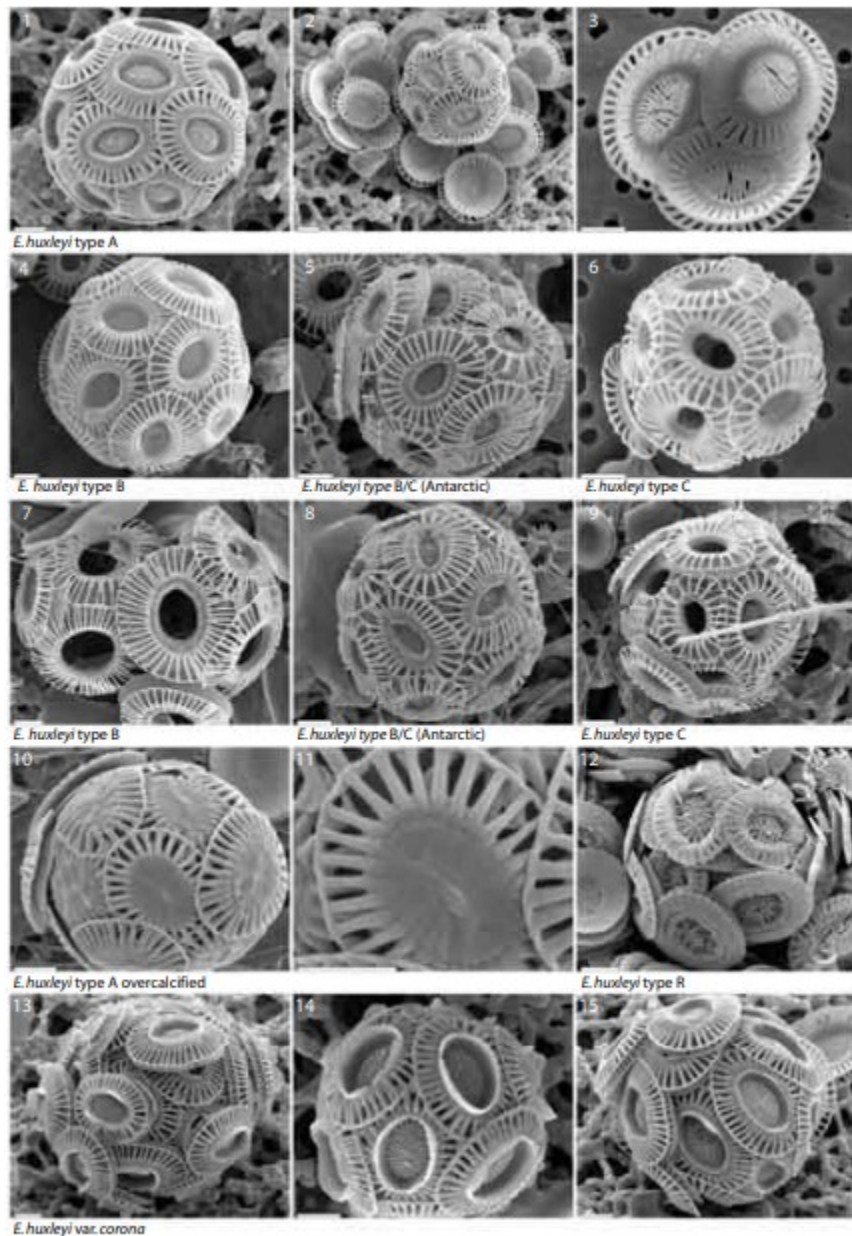
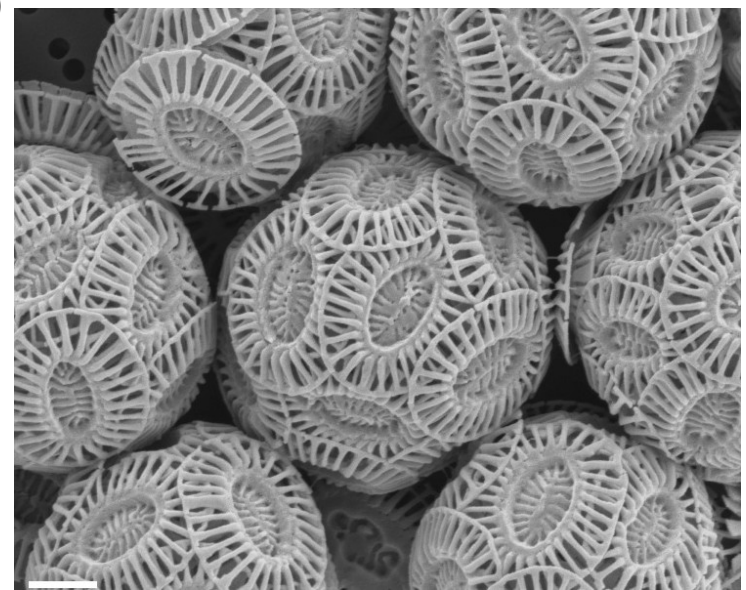
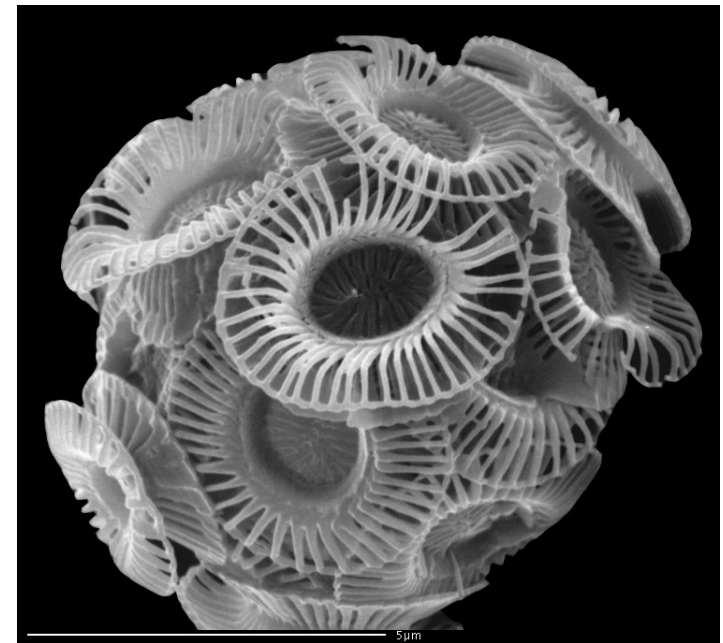


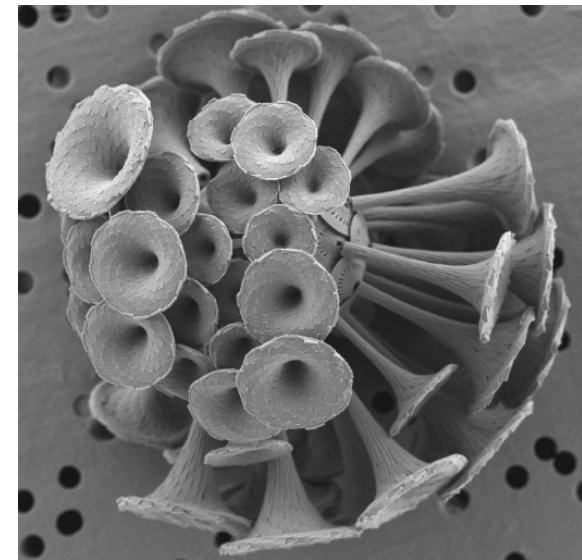
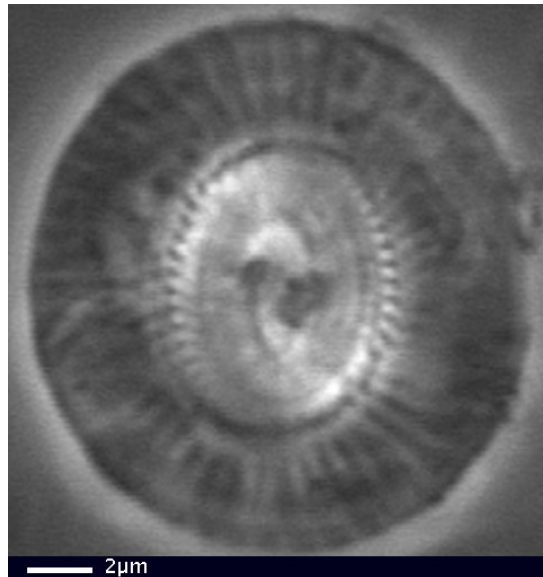
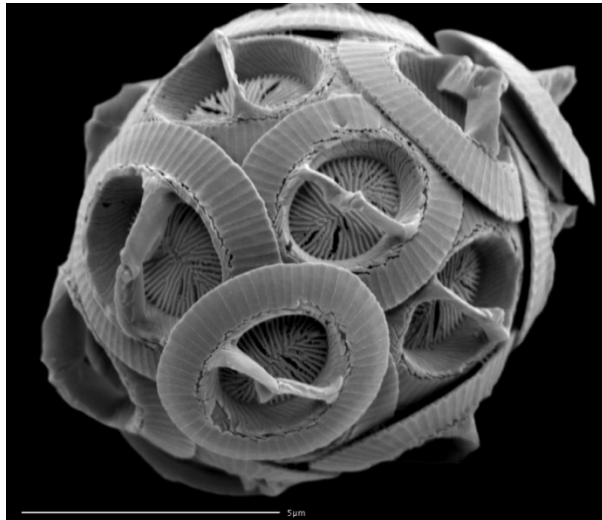
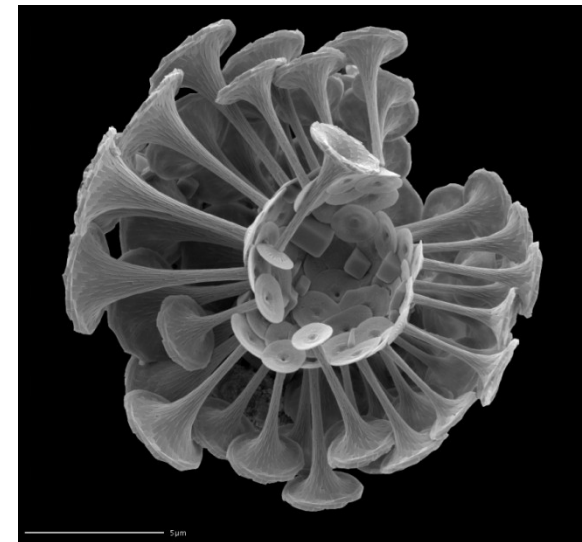
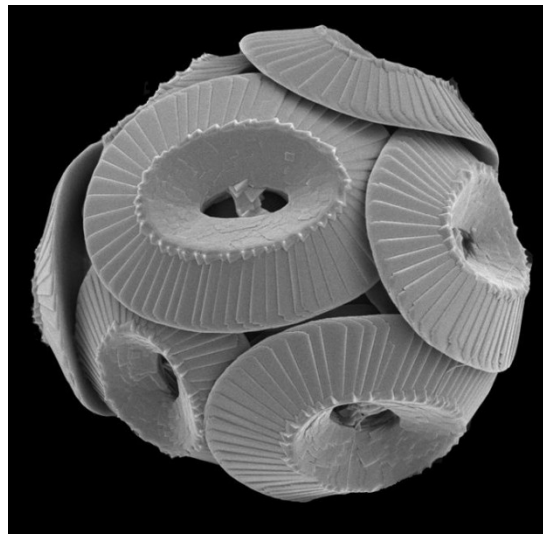
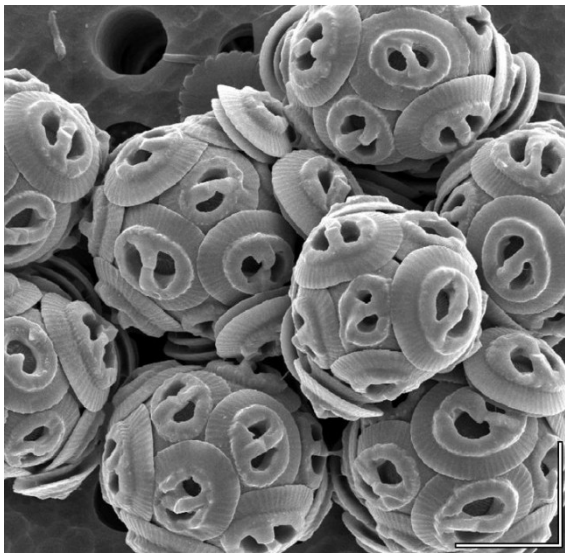
Plate 1 - Noelaerhabdaceae: *Emiliana*



*E. hux* type A



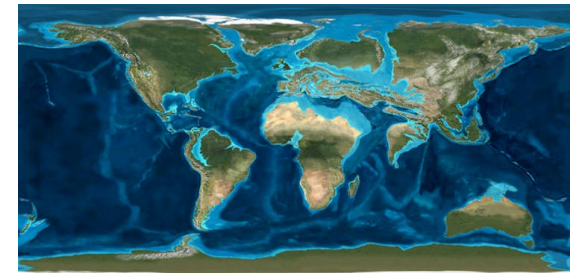
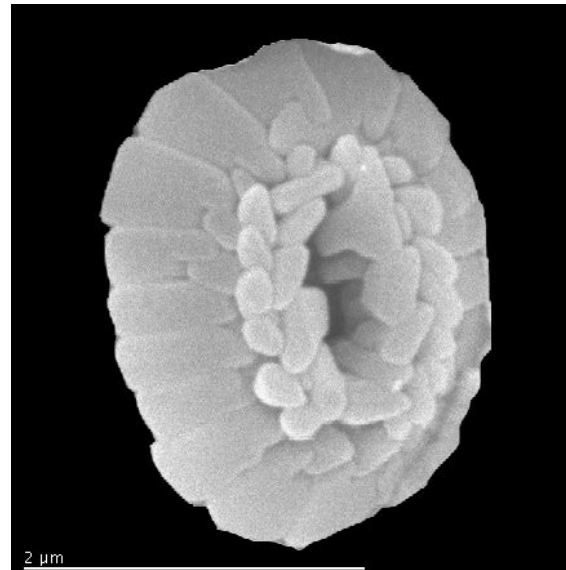
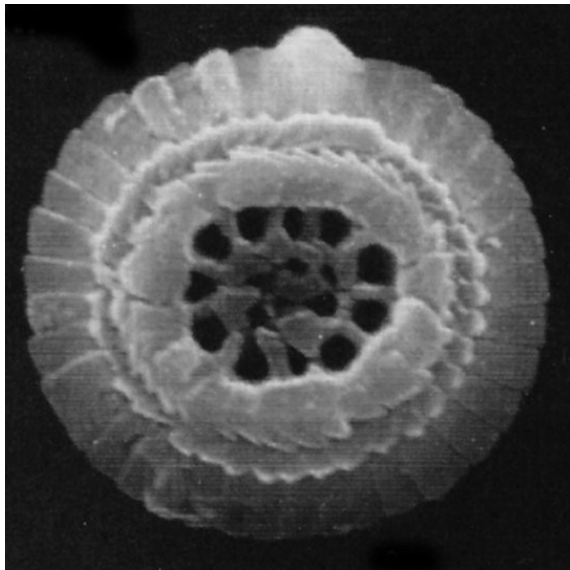
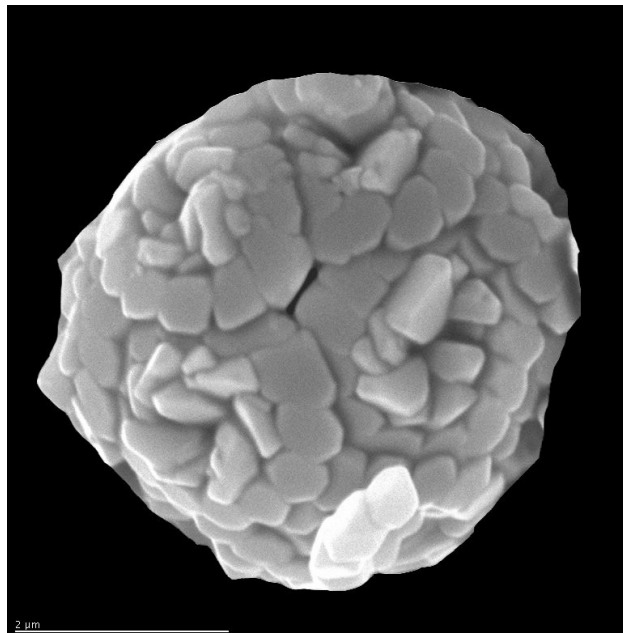
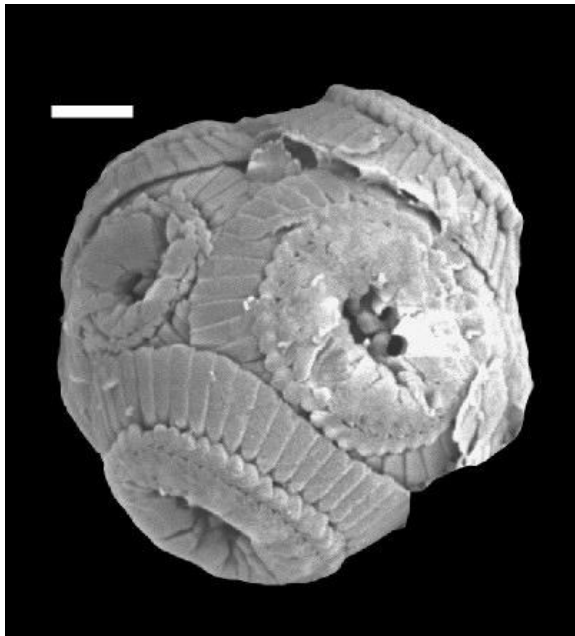
*E. hux* type B



*Gephyrocapsa oceanica*  
(Isochrysidales, Noelaerhabdaceae)  
- 7.3 my to recent

*Coccolithus pelagicus*  
(Coccolithales, Coccolithaceae)  
- 66 my to recent

*Discosphaera tubifera*  
(Syracosphaerales, Rhabdosphaeraceae)  
- 16 my to recent

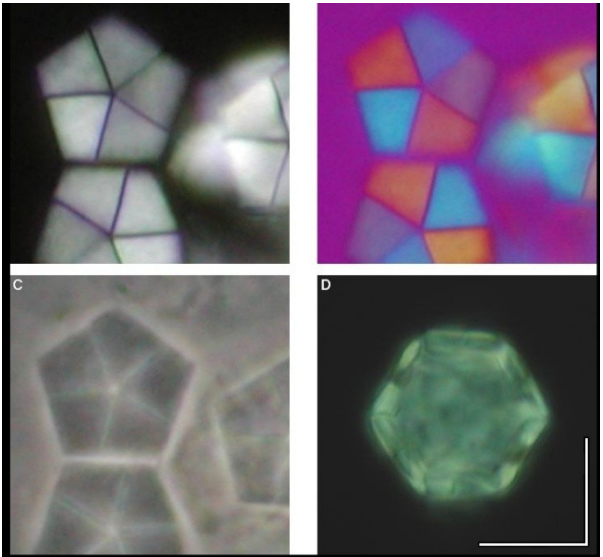
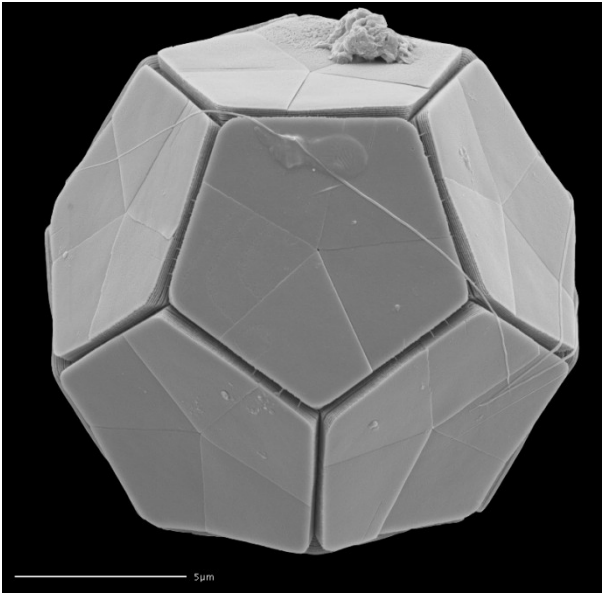


Eocene ocean

*Toweius pertusus*  
(Isochrysidales, Prinsiaceae)  
- 65 to 46 my ago

*Prinsius dimorphosus*  
(Isochrysidales, Prinsiaceae)  
- 66 to 56 my ago

# Braarudosphaerales



Braarudosphaera bigelowii  
(Braarudosphaeraeae)  
- 100.5 my to recent

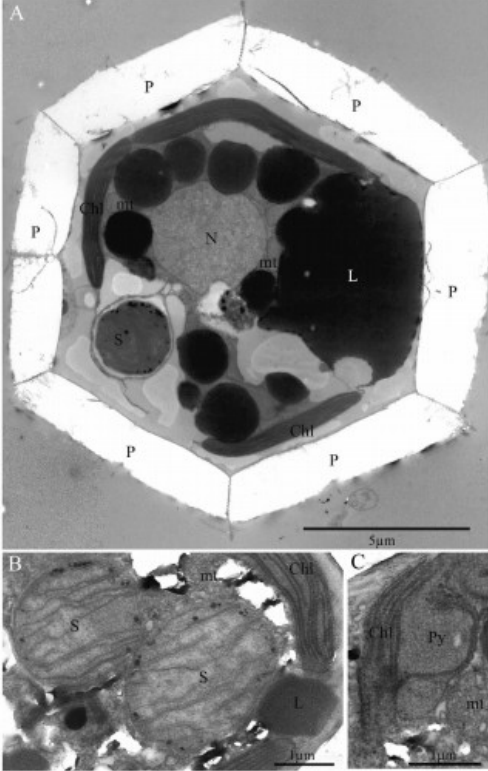


**Figure 2. TEM images of *Braarudosphaera bigelowii* specimens -A and -B.** (A) *B. bigelowii* specimen-B from offshore Tomari port, Tottori showing nucleus (N), chloroplasts (Chl), lipid globules (L), pentaliths (P), mitochondria (mt) and spheroid body (S). (B) *B. bigelowii* specimen -A from Tosa 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

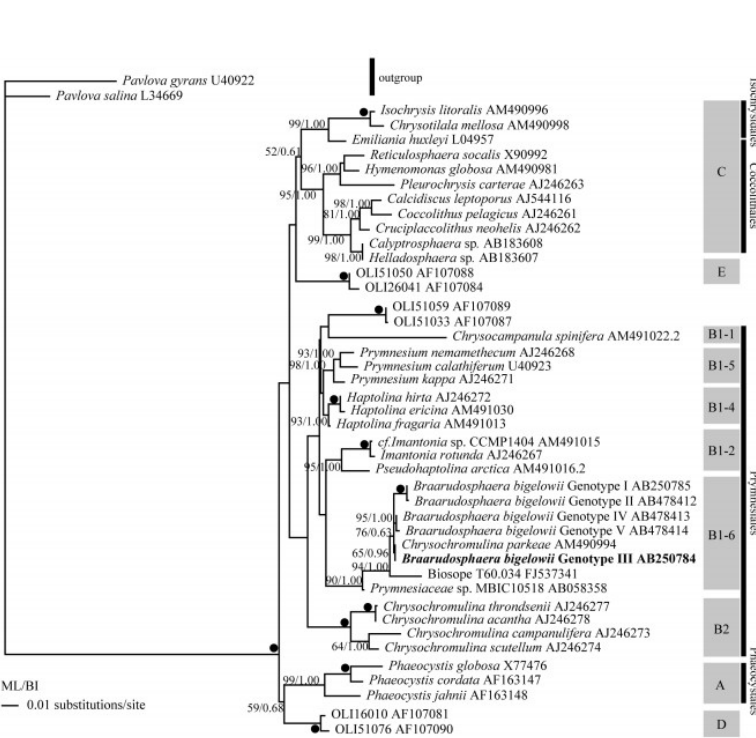
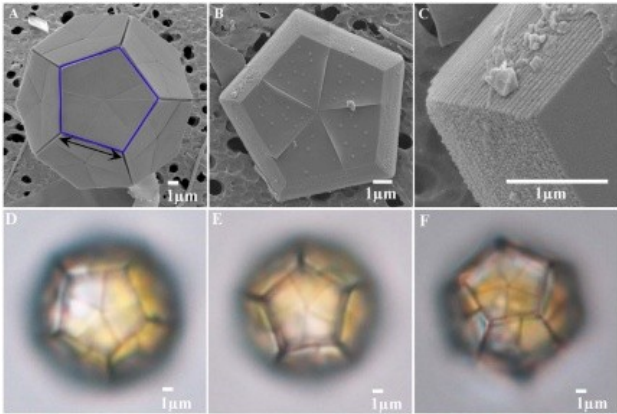
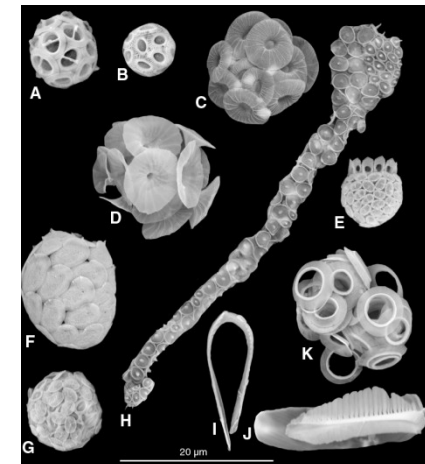
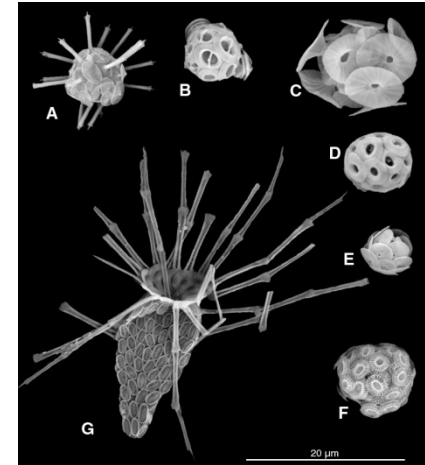
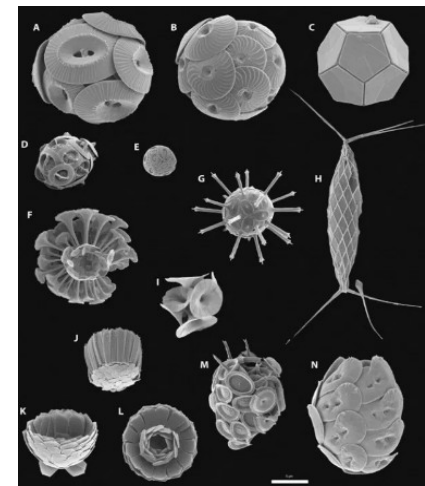


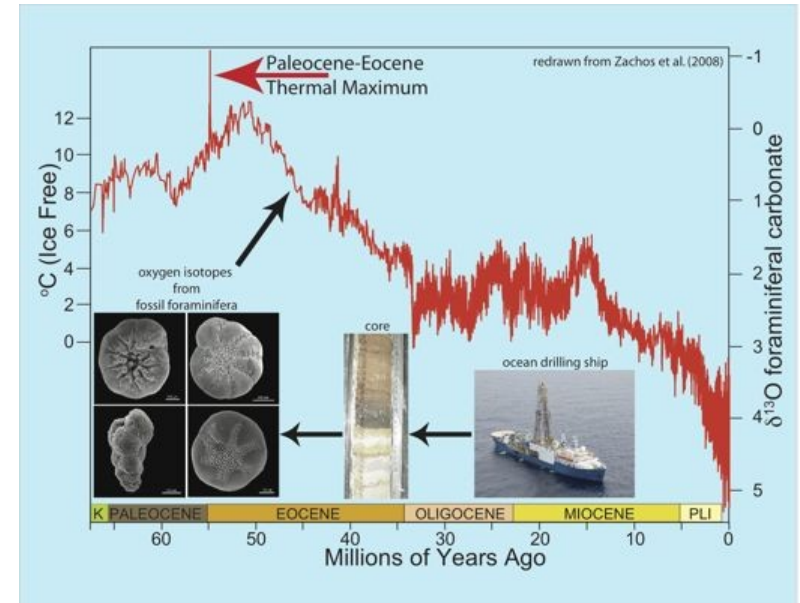
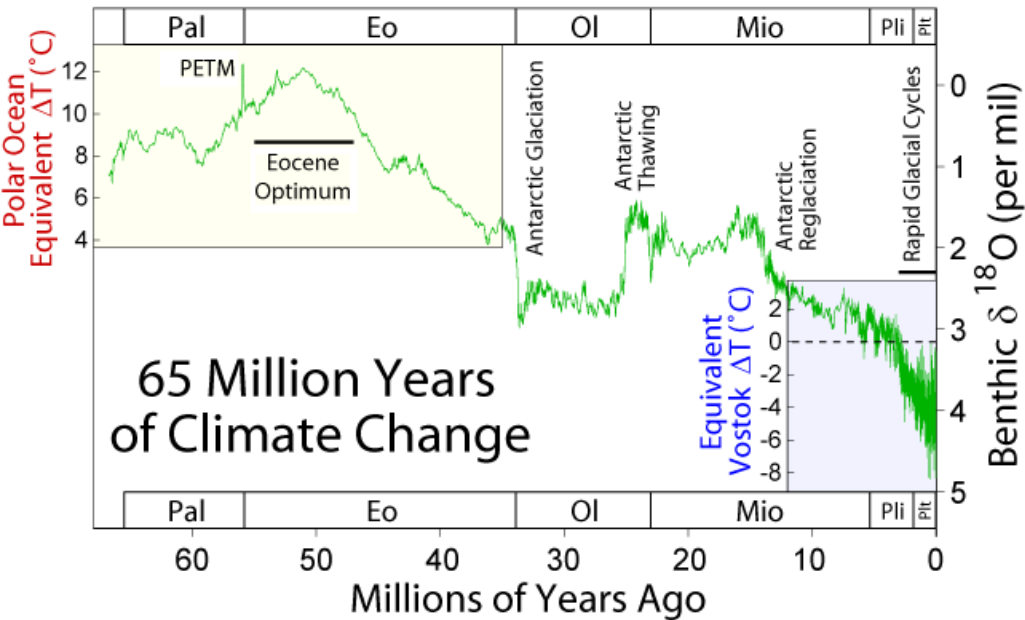
**Figure 4. Phylogenetic tree based on 18S rDNA sequences using the Maximum Likelihood method.** Representatives of the Pavlovophyceae were used as an out-group. Asterisks refer to the clade names of Edvardsen et al. [24]. The numbers on each node indicate the bootstrap values from ML analysis and posterior 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

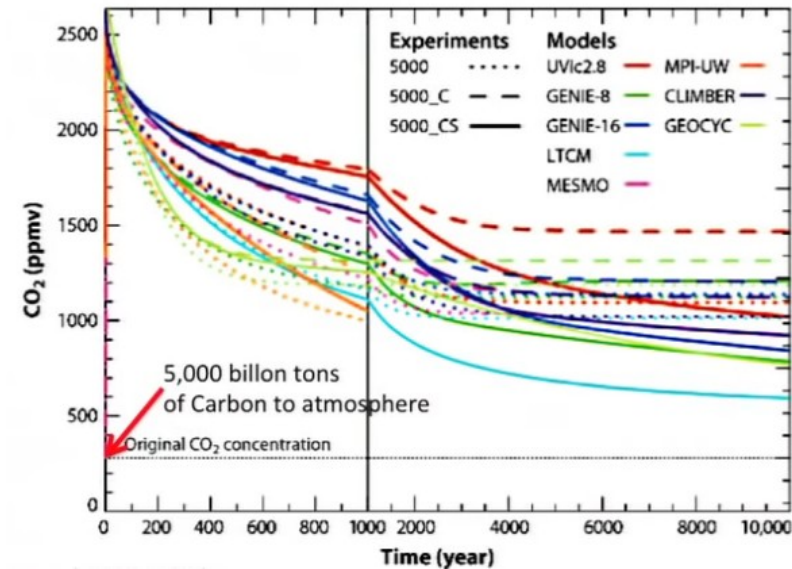
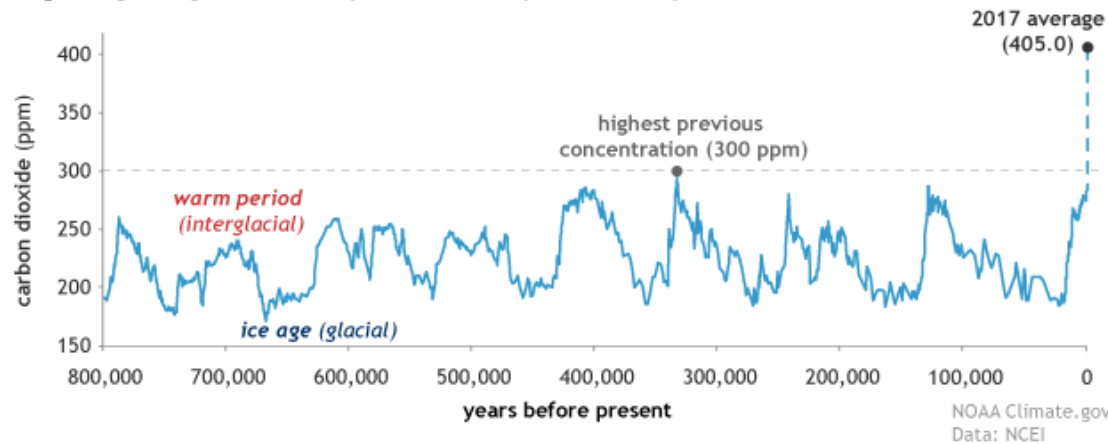
# Coccolithophores and global calcification



# global climate and the carbon cycle

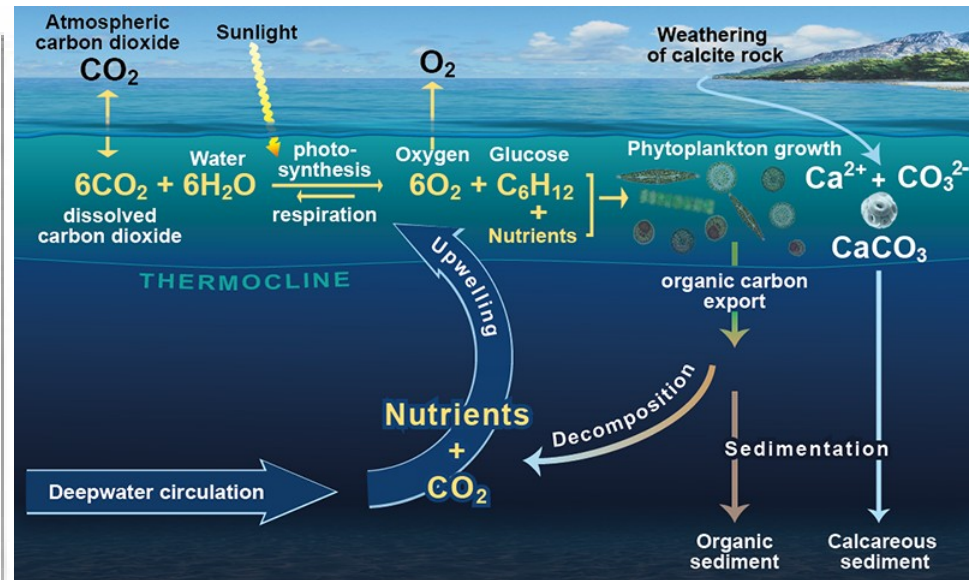
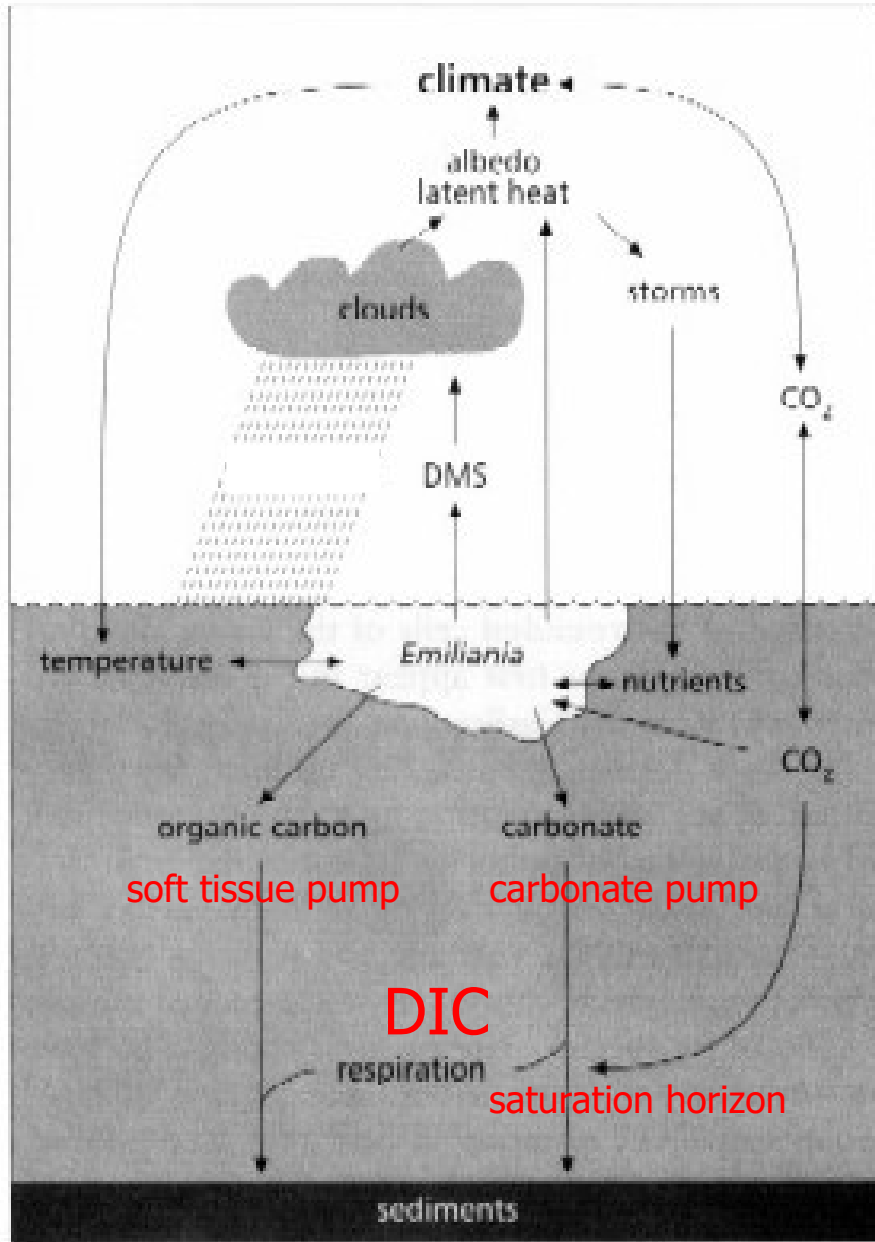


CO<sub>2</sub> during ice ages and warm periods for the past 800,000 years



calcifying organisms, such as Coccolithophores, provide long-term carbon sink mechanisms, compensating for instantaneous CO<sub>2</sub> excursions

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



calcification:

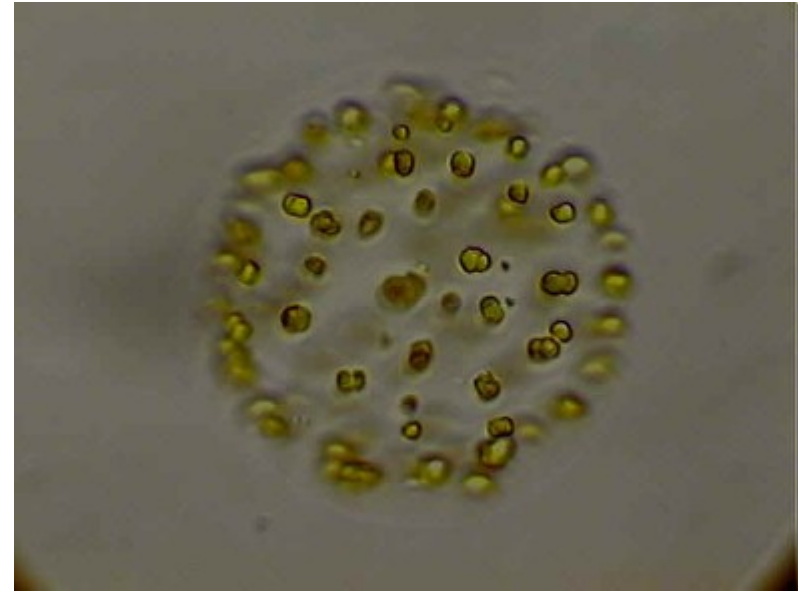
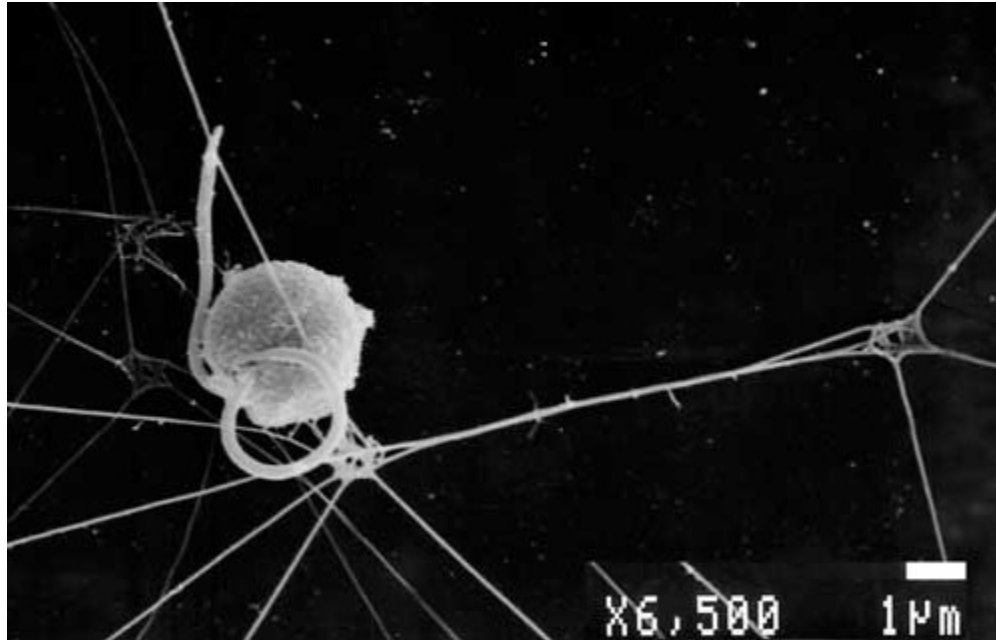


only about 0.5% of CaCO<sub>3</sub> produced at the surface reaches the ocean floor

DIC is about 15% higher in ocean depths and this is of key importance for atmospheric CO<sub>2</sub> levels

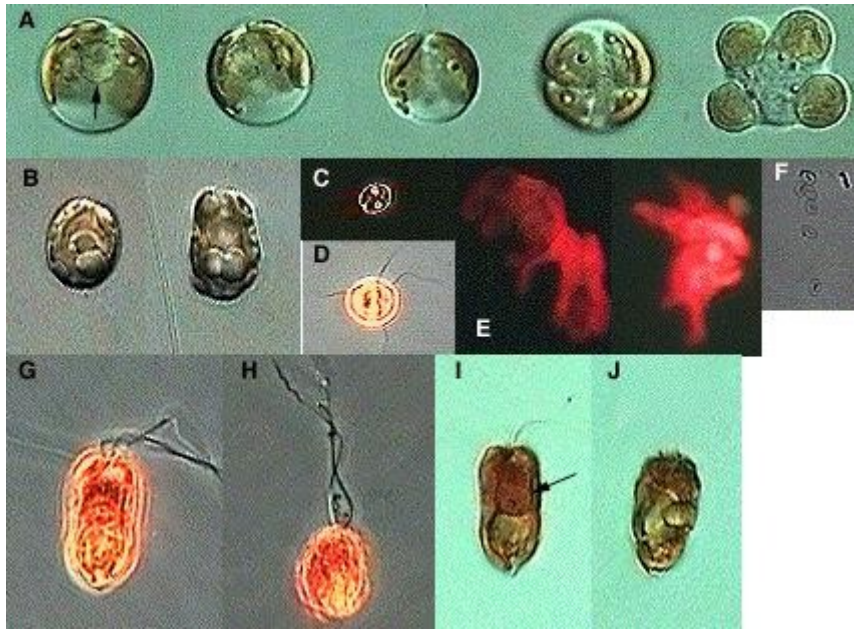
saturation horizon – below which CaCO<sub>3</sub> dissolves

# *Phaeocystis* – flagellate with sticky chitinous filaments

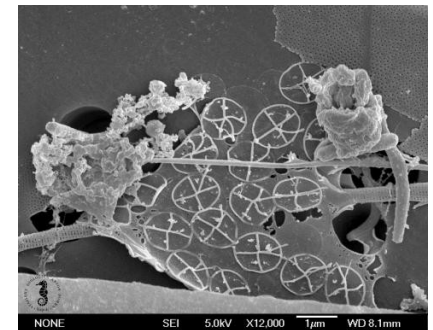
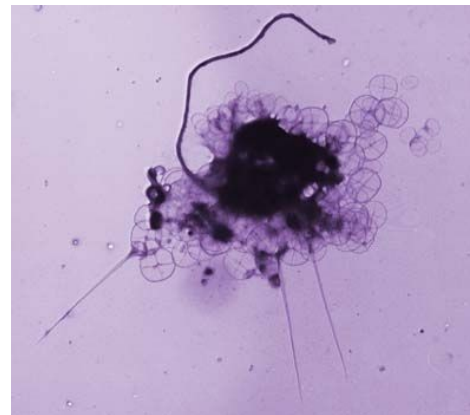
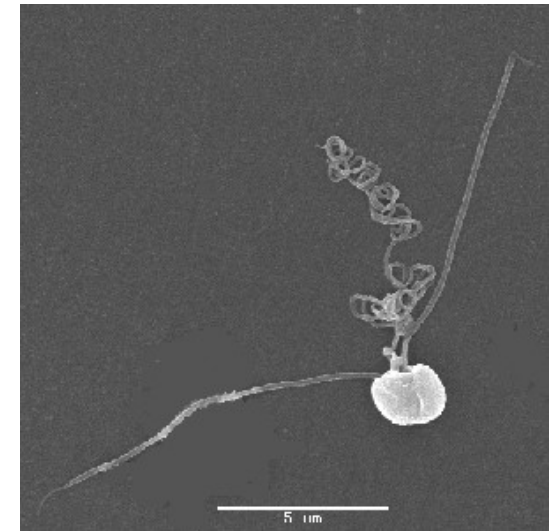


genus *Phaeocystis* - ca 10% of global DMS production, coastal white tides

# Chrysochromulina



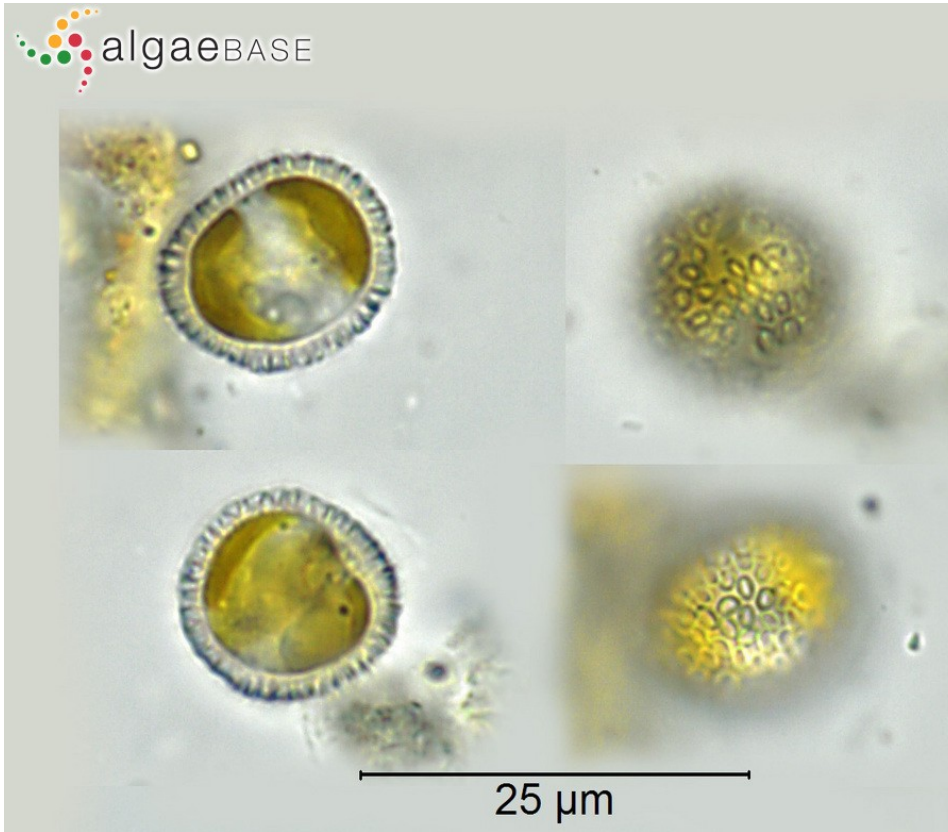
zdroj: [nordicmicroalgae.org](http://nordicmicroalgae.org)



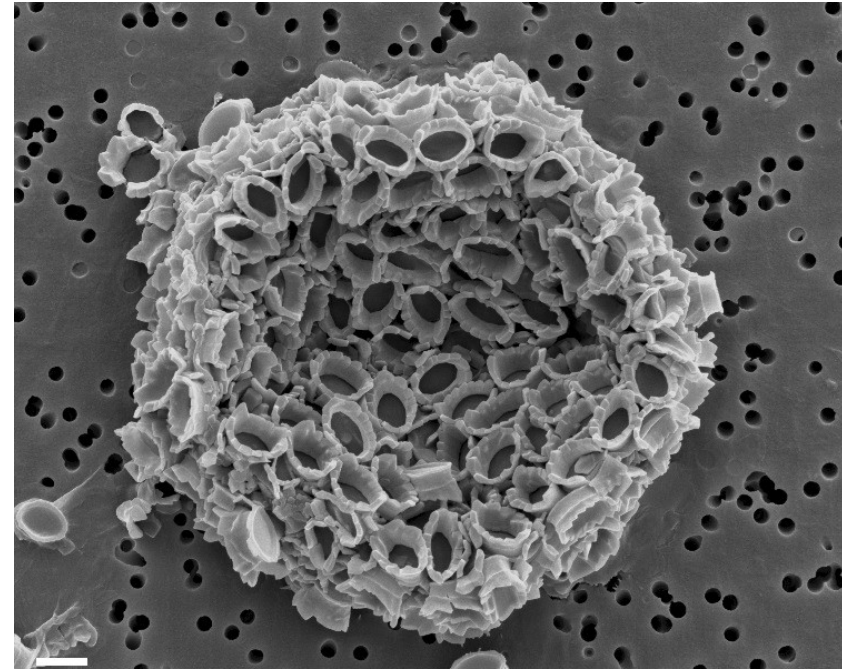
unicellular, planktonic marine [rarely freshwater] flagellates  
 haptonema usually prominent – attachment to the substrate or to the prey  
 mixotrophy - phagotrophy, osmotrophy

organic scales

# ***Hymenomonas*** - a freshwater coccolithophore genus



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



occurs in oligotrophic phytoplankton

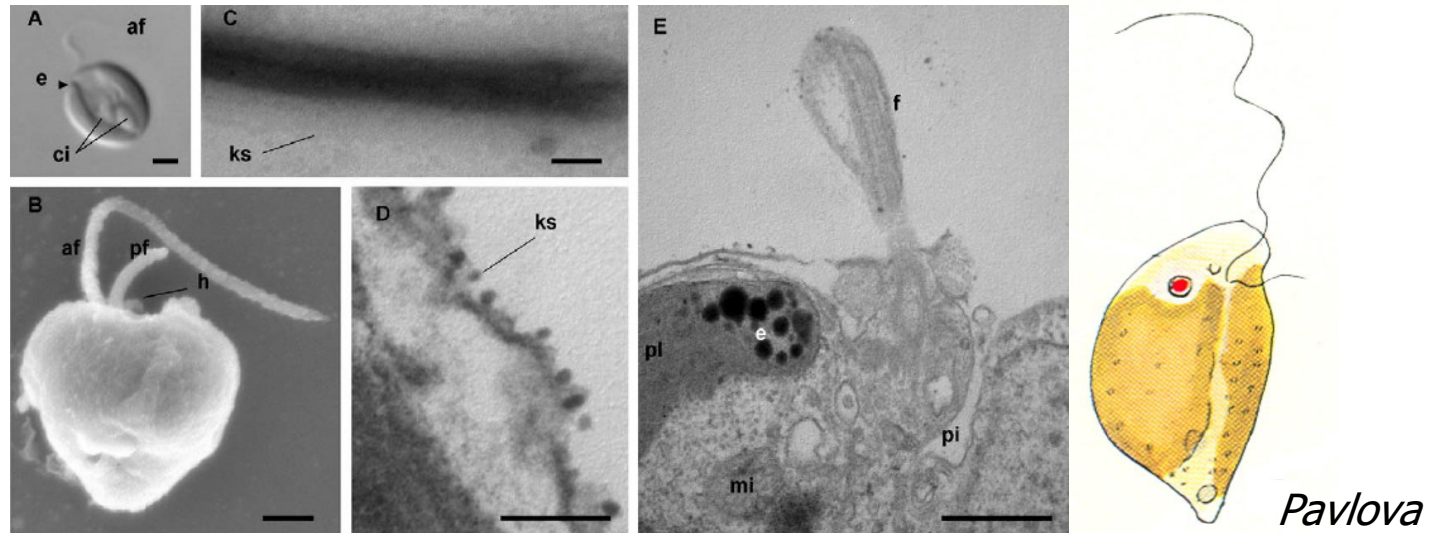
# Pavlovophyceae - non-calcified flagellates, incl. some brackish and freshwater taxa

*Exanthemachrysis*

*Pavlova*

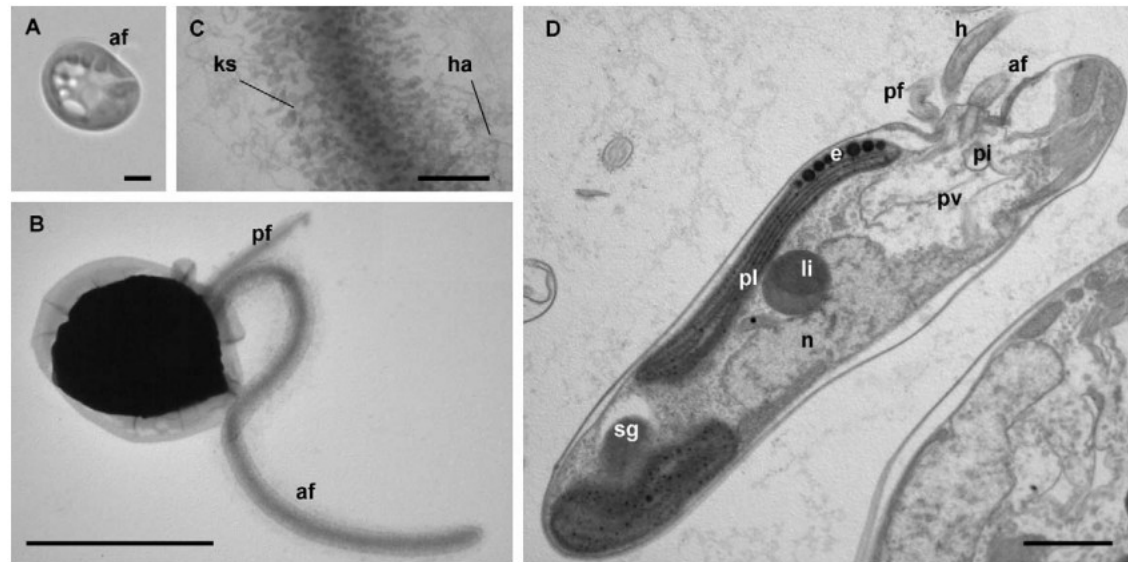
*Rebecca*

*Diacronema*



*Rebecca salina*

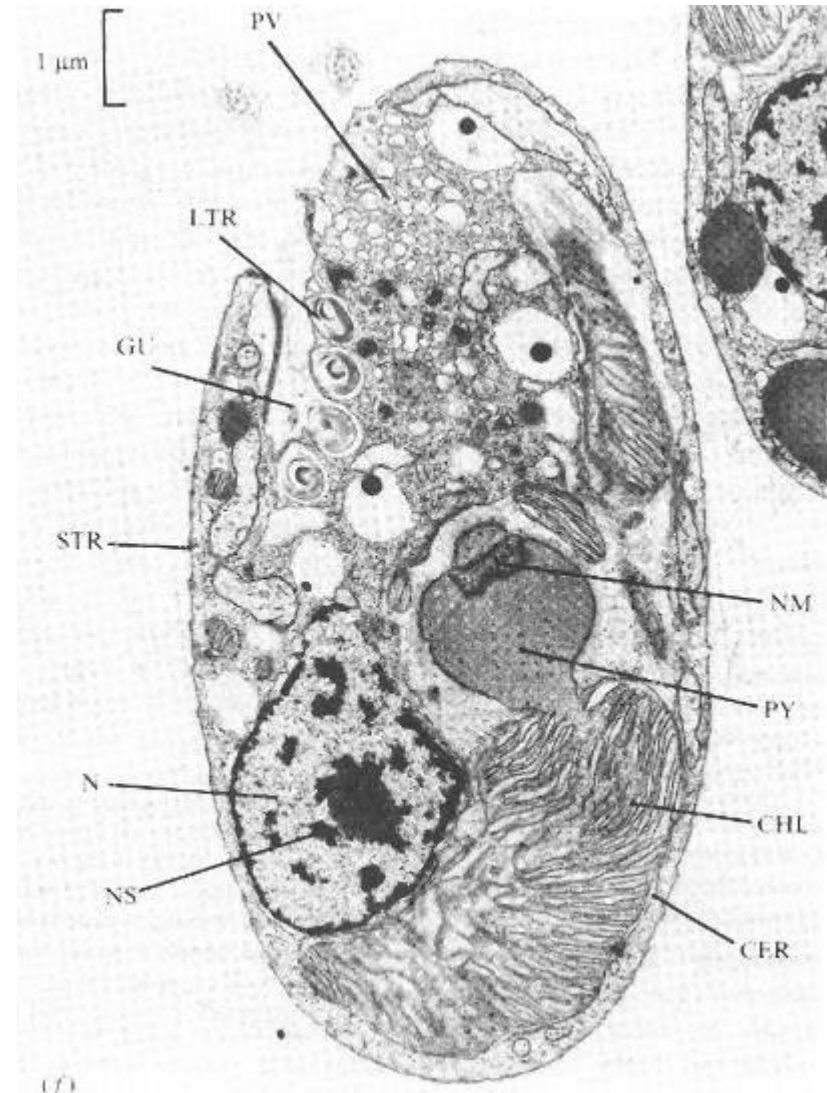
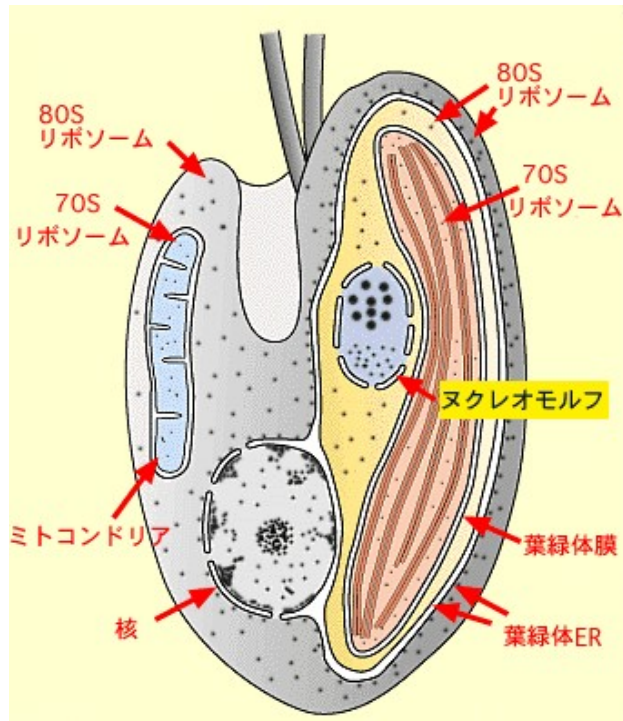
*Bendif et al., 2011, Protist*



*Diacronema (Corcontochrysis) noctivaga*

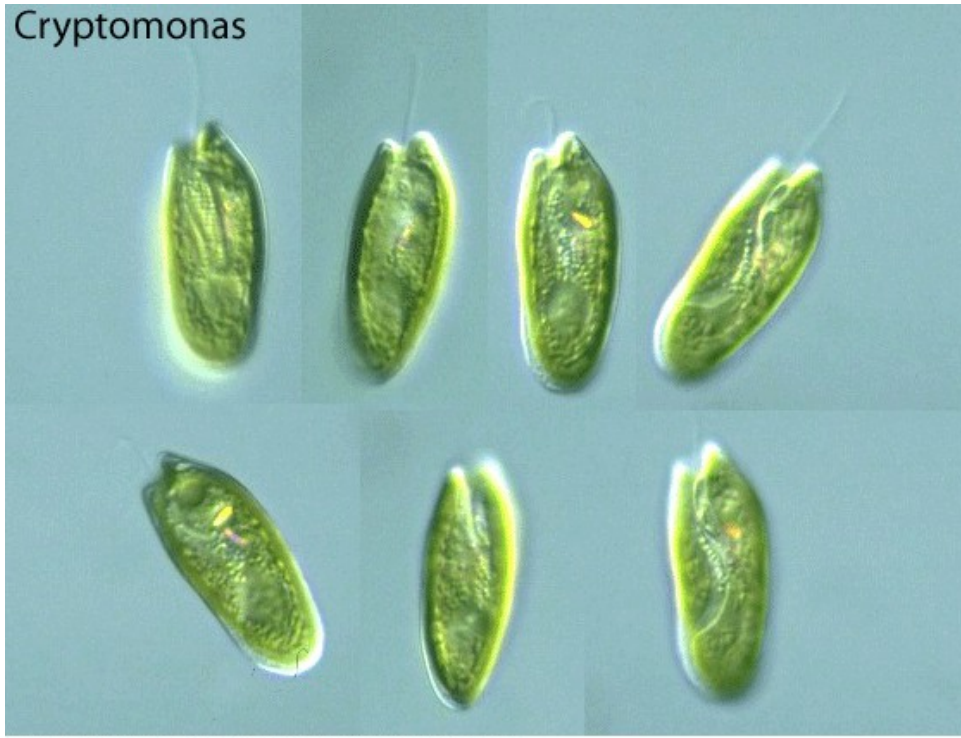
# Cryptophyta

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



plankton of freshwater and seas, about 200 species

## *Cryptomonas* – most frequent freshwater genus



© Y. Tsukii, see [http://protist.i.hosei.ac.jp/Protist\\_menuE.html](http://protist.i.hosei.ac.jp/Protist_menuE.html)



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

