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This Biology Honors Thesis

Construction of Dichotomous Taxonomic Keys for San Francisco Bay Planktonic Diatoms

by

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is submitted in partial fulfillment of the requirements for the

Biology Honors Program

at the

University of San Francisco

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ABSTRACT

Planktonic diatoms exhibit high biodiversity in marine systems and make a significant contribution to water column primary productivity. This makes research on planktonic diatoms particularly important in measuring the health of coastal marine ecosystems. At the University of San Francisco (USF), undergraduate research has been conducted since September 2015 to study planktonic diatoms in San Francisco Bay. A previous study by Keith (2018), Planktonic Diatom Species Succession in San Francisco Bay, documented changes in species diversity over time, observing seasonal patterns in species richness as well as the effect of environmental factors such as salinity, temperature, and rainfall on species succession. In her work, an abundance of centric diatoms was present, indicating their essential role in local phytoplankton communities; however, the majority of observed centric taxa could not be identified with light microscopy. The current project was intended to use scanning electron microscopy to examine phenotypic characteristics of cells from field collections of Keith (2018) and clonal cultures to identify the species that make up the assemblage of dominant centric diatoms. Five centric diatom species were identified prior to the COVID-19 pandemic: *Coscinodiscus curvatulus, Actinoptychus senarius, Coscinodiscus oculus-iridis, Coscinodiscus lentiginosa,* and *Thalassiosira nordenskioeldii.* However, due to temporary sampling site closures and limited access to laboratories because of stay-at-home orders from the pandemic, the project was modified to be done remotely. The project was modified to analyze and compile present literature on diatom taxonomy based on morphology and develop taxonomic keys specific to diatoms in San Francisco Bay for use by both specialists and non-specialists, including school-aged children. In the construction of the keys, genera and species were considered significant if they were observed in ≥50% of the samples in the study by Keith (2018) from September 2015 - December 2017, including *Chaetoceros* spp., *Ditylum brightwelli, Pseudo-nitzschia* spp., *Rhizosolenia setigera, Skeletonema costatum, Thalassiosira* spp., and *Trieres mobiliensis*. Here, two keys are constructed – “A Technical Key to Common Planktonic Diatoms in San Francisco Bay” and "A Basic Key to Common Phytoplankton in San Francisco Bay” – and the challenges of constructing the keys are discussed. These keys will aid in the assessment of diatom biodiversity in San Francisco Bay. Additionally, open-source diatom taxonomy websites have been collected to further support specialists and non-specialists in their scientific education and study of phytoplankton.

INTRODUCTION

At the University of San Francisco (USF), undergraduate research has been conducted since September 2015 to study planktonic diatoms in San Francisco Bay. Diatoms are single-celled photosynthetic aquatic organisms in the division of Chrysophyta and the class of algae known as Bacillariophyceae (Cupp, 1943, Perry 2003). They have rigid cell walls with intricate designs made of silica (SiO_2) glass (Cupp 1943, Perry 2003). While some diatoms are found solitary, or not attached to other diatoms, some can be linked to one another in a chain via filaments and some are pseudofilamentous, meaning that the cells are held together in a line by a gelatinous layer (Scott and Marchant 2005). Sometimes this gelatinous layer can result in clusters or colonial aggregations (Scott and Marchant 2005). Diatoms are likely to be cosmopolitan and can live in a variety of environments including freshwater, brackish water, and saltwater as well as in ice and damp places such as soil (Cupp 1943, Malviya et al. 2016). Marine species, in particular, can be pelagic (water column) or benthic (associated with substrates) (Boyer 1927, Cupp 1943). Depending on where they live and reproduce, pelagic species can also be further classified as either *oceanic* if in the open ocean or *neritic* if close to the coast (Cupp 1943). This division between oceanic and neritic pelagic species is not clear as some oceanic species may be found and collected near the coast and some neritic species may be found and collected in the open ocean. In general, most diatoms tend to be found in nutrient-rich waters, upwelling zones, and coastal waters (Busseni et al. 2020, Leblanc et al. 2012, Malviya et al. 2016).

Diatoms are also a major group of phytoplankton due to their significant contribution to global primary production (**Figure 1**) (Cloern and Dufford 2005, Falkowski et al. 1998). They produce up to 50% of the oxygen we breathe through photosynthesis and regulate atmospheric levels of carbon dioxide; it has also been found that chlorophyll concentration and phytoplankton species composition are correlated with ocean circulation and essential nutrient fluxes (Falkowski et al. 1998). Additionally, diatoms serve as important energy sources for the aquatic food chain system (Cloern and Dufford 2005, Perry 2003, Schabhüttl et al. 2011). In marine ecosystems, phytoplankton form the base of the food web (Scott and Marchant 2005). In particular, diatoms are rich in eicosapentaenoic acid (EPA), an essential fatty acid that increases in concentration with phytoplankton size (Cloern and Dufford 2005, Jónasdóttir 2019, Kainz et al. 2004). EPA has been found to be important for aquatic food web trophic transfer efficiency and may be correlated with the somatic growth of some planktonic organisms and fish larvae, making them a highly nutritional source of energy for fauna in the ocean (Jónasdóttir 2019, Kainz et al. 2004). Since San Francisco Bay is a nutrient-rich estuary, blooms of diatoms occur where cells divide at a faster rate than those that die off, resulting in a diatom-dominated phytoplankton community (Cloern and Dufford 2005). The significant diatom presence in the community could be why there is a higher efficiency of fish production in marine-estuary systems like San Francisco Bay compared to freshwater systems (Cloern and Dufford 2005, Keith 2018).

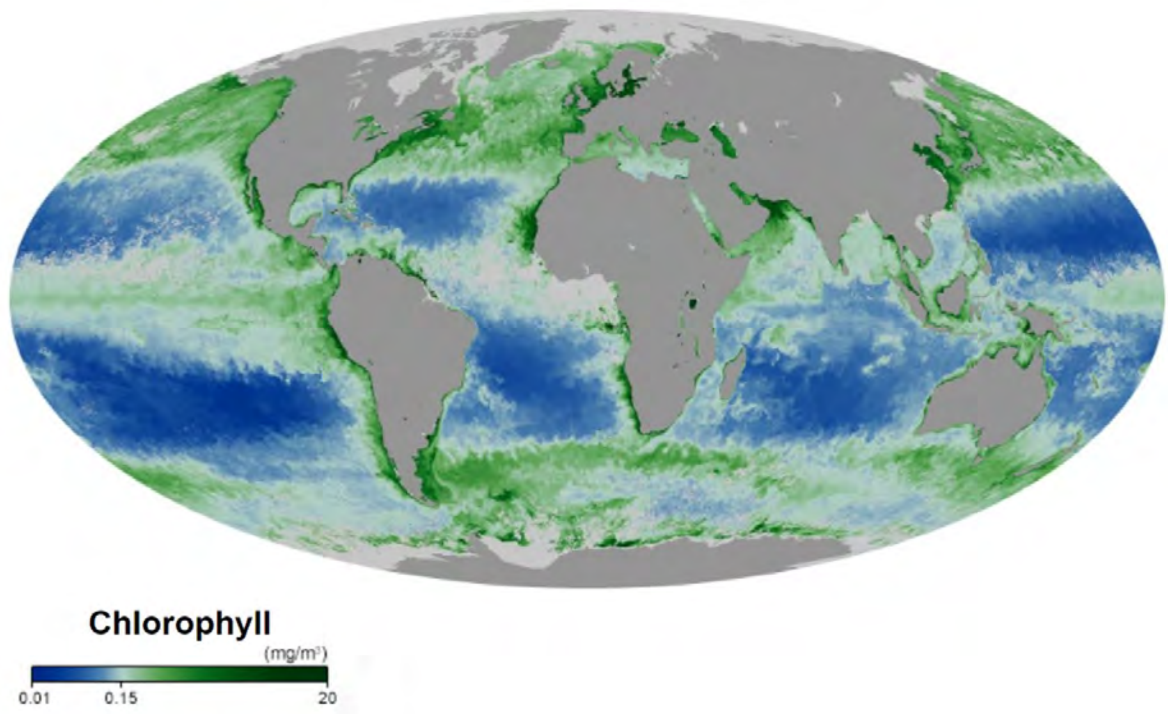


Figure 1. Ocean chlorophyll concentration as an indicator of marine primary production in March 2021. Green indicates high phytoplankton concentration. Blue indicates low phytoplankton concentration (NASA Earth Observatory 2021).

Additionally, some species tend to be more abundant depending on the time of year or the season (Cupp 1943, Keith 2018, Scott and Marchant 2005). A previous study by Keith (2018), Planktonic Diatom Species Succession in San Francisco Bay, documented changes in species diversity from 2015 - 2017, observing seasonal patterns in phytoplankton species richness as well as the effect of environmental factors such as salinity, temperature, and rainfall on species succession. Furthermore, a study by Cloern and Dufford (2005) found that diatoms accounted for 81% of the cumulative biomass of their phytoplankton samples. These taxa are, therefore, an important component of the San Francisco Bay ecosystem.

Diatom structure and classification

The classification of diatom species has largely been based on morphology, or the physical structure and characteristics of the cell walls (Pappas 2006). Although some molecular techniques such as ribosomal RNA and genomic DNA sequencing have shown promise in providing more precise species identification, these techniques are currently limited by available sequence information, so morphology is often the primary method of species identification (Hoppenrath et al. 2007, Leliart 2021, Scott and Marchant 2008, Williams et al. 2011). Particular ornamentation or appendages such as tube-like processes; patterns of areolae or pores on the cell (which form striae or lines of pores); presentation in chains, clusters, or solitary; the shape of the frustule; and many more characteristics unique to a specific diatom species are indicators which aid in the identification of species (Boyer 1927, Cupp 1943, Simonsen 1975). All diatoms, however, share a basic cell structure.

The cells walls of diatoms are made up of pectin and silica, a glass-like material (Cupp 1943, Perry 2003). Each cell is made up of two parts called valves (or frustules) which fit into each other like a box and lid or, in the case of centric diatoms, like a petri dish (**Figure 2**). Centric diatoms have radially symmetric valves where the striae are arranged around a central point (Tomas et al. 1997). By contrast, pennate diatoms have bilaterally symmetric valves where the striae are arranged in relation to a line (Tomas et al. 1997). The epivalve is the larger valve or "lid" and the hypovalve is the smaller valve or "box" (Perry 2003, Ross et al. 1979). The valve face or surface refers to the flat side of the "lid" or "box", and the valve mantle refers to where the valve face bends at a 90-degree angle to begin forming the curved walls of the "lid" or "box" (Ross et al. 1979, Simonsen 1975). The other part of the curved walls which gives the cell more height is called the girdle and is made up of connecting/girdle bands which are collectively called the cingulum (Cupp 1943, Tomas et al. 1997). The epicingula refers to the cingulum associated with the epivalve, and the hypocingula refers to the cingulum associated with the hypovalve. Theca refers to the valve and the cingulum together; the epitheca includes the epivalve and the epicingula, and similarly, the hypotheca includes the hypovalve and the hypocingula (Tomas et al. 1997).

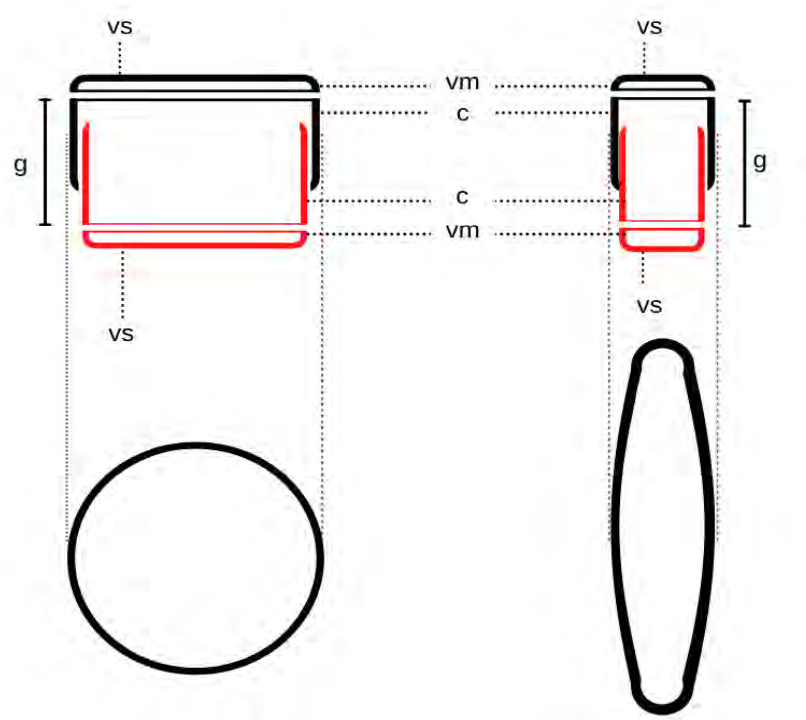


Figure 2. Diagram of the basic structure of a centric diatom (left) and a pennate diatom (right). Upper cells are in girdle view with black indicating the epitheca and red indicating the hypotheca. Lower cells are in valve view. Abbreviations: *vs*, valve surface; *vm*, valve mantle; *c*, cingulum or connecting/girdle bands; *g*, girdle (Adapted from Cupp 1943).

Cell reproduction and division

During asexual or vegetative cell division, the diatom cell first increases in volume. Once the cell reaches a maximum volume, mitosis and cytokinesis split the cell such that the epitheca and hypotheca separate (Cupp 1943). Once separated, each original or parent epitheca becomes the epitheca of one of the new cells, gaining a new hypotheca. The original hypotheca becomes the epitheca of the other daughter cell. This means that as the cells continue to divide, some daughter cells will get smaller in size while other daughter cells will remain the original size; this phenomenon is referred to as the MacDonald-Pfitzer hypothesis (Kale and Karthick 2015). At some point, the cells that are getting smaller will reach a minimum size range where sexual reproduction is necessary and the formation of auxospores grows the cell back to a maximum volume (**Figure 3**).

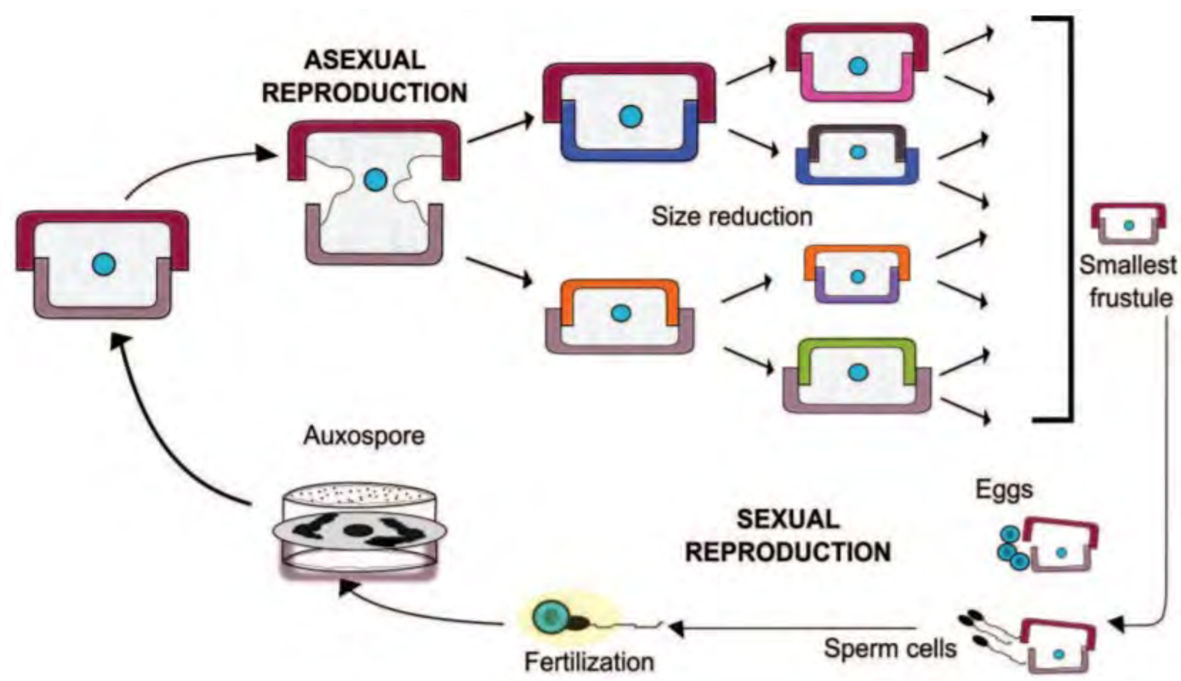


Figure 3. Diagram of diatom asexual and sexual reproduction (from Kale and Karthick 2015).

Variance in diatom classification

Present literature regarding the characterization of certain diatom species shows a variance in classification. The constantly changing nature of taxonomy contributes to this variance. There are several reasons why taxonomy is always changing. One reason is the advancements in technology, such as improved electron microscopy which allows for a more detailed analysis of morphological characteristics of diatom species as well as DNA sequence analyses that further inform taxonomy through molecular markers (Hoppenrath et al. 2007, Leliart 2021, Scott and Marchant 2008, Williams et al. 2011). These technological advancements have led to the discovery of hundreds of new species (Leliart 2021). However, if DNA sequence information and morphological descriptions of species are not used in tandem, then inconsistencies may arise in identifying species, and in some cases, some lineages may be unnamed (Leliart 2021). Another reason taxonomy changes is due to the increased availability of data and information. For example, morphological data collected from samples on one side of the world may look slightly different from data collected from samples on the other side of the world due to reproductive isolation (Pappas 2006). Additionally, speciation events are an ongoing process, making defining clear species boundaries more difficult (Leliart 2021, Pappas 2006). Ultimately, challenges in taxonomy have resulted in variable information for many diatom species classifications (Pappas 2006).

Properly identifying species and understanding diatom taxonomy are important because, compared to larger organisms, diatoms exhibit much higher biodiversity within an ecosystem; it is estimated that there are between 1,800 to 200,000 diatom species, although recent global estimates recognize a range of 12,000 to 30,000 diatom species as well as approximately 285 genera (Cupp 1943, Malviya et al. 2016, Scott and Marchant 2005, Williams et al. 2011). It is estimated that around 100,000 diatom species have not been discovered yet (Fischer and Bunke 2001). Differences in species composition in response to geography, season, climate, and ocean conditions suggest that individual species may serve as indicators of environmental changes (Keith 2018, Pappas 2006, Scott and Marchant 2005).

Guides on diatom taxonomy

Species identifications and classification serve as the basis for phylogenetic studies through the discovery of monophyletic groups by determining synapomorphies, or defining characteristics - whether morphological or molecular - of a particular lineage (Williams et al. 2011). Therefore, taxonomy and the proper identification of species are essential in assessing biodiversity and the distribution and evolution of species (Hoppenrath et al. 2007, Leliart 2021). Williams et al. (2011) assert that several principles should be considered to further the progress of diatom classification: explicit determination of characteristics, recognition and analysis of synapomorphies, recognition of only “demonstrable monophyletic groups,” and “analyses of *all* data sources made explicit and repeatable” (Williams et al. 2011). Many existing guides on taxonomy have attempted to compile the widely variable diatom taxonomic literature in accordance with the last principle.

For example, Tomas et al. (1997) developed a manual for identifying marine diatoms and dinoflagellates. This manual organized species alphabetically within genera and families and used an outline with page numbers to guide users through the manual in a text version of a decision tree (Tomas et al. 1997). Scott and Marchant (2005) analyzed taxonomic literature on Antarctic pelagic protists and created a guide, focused towards non-specialists, to clarify confusion over taxonomy. However, similar to Tomas et al. (1997), this guide was not in the form of visual taxonomic decision trees but rather as a collection or catalog of illustrated descriptions of Antarctic species with taxa listed alphabetically within genera and families (Scott and Marchant 2005). Cupp (1943) created a manual for the identification of marine plankton diatoms on the West Coast of North America, but similar to the other guides, the manual was not created as a taxonomic key but rather as a catalog of illustrated descriptions of species.

Currently, there are no formal guides for phytoplankton in San Francisco Bay. However, there are several groups of people in San Francisco Bay Area that are studying and looking at San Francisco Bay phytoplankton. A list of phytoplankton species has been compiled from 1992 - 2014 by the United States Geological Survey (USGS) (Nejad et al. 2017), but this list does not explain how to identify these species found in San Francisco Bay. The Gulf of Farallones Visitor Center has marine education programs for children ranging from kindergarten through high school that sample and examine San Francisco Bay phytoplankton (NOAA 2017). Additionally, the Kudela Lab at the University of California Santa Cruz has developed an online catalog of phytoplankton in Monterey Bay which has a similar species composition to what is seen in San Francisco Bay (Kudela Lab at the University of California Santa Cruz 2021).

Since the San Francisco Bay phytoplankton community is diatom-dominated, and there is an observed pattern of species composition with climate, season, time of year, and ocean conditions, diatoms clearly play a significant role in the Bay ecosystem. Understanding species dynamics and why these ecological and biogeochemical patterns occur necessitates an evaluation of biodiversity (Cloern and Dufford 2005, Schabhüttl et al. 2011). However, in order to analyze biodiversity, taxonomy needs to be clarified. Here, the present literature on diatom taxonomy based on morphology is analyzed and compiled to develop two taxonomic keys specific to diatoms in San Francisco Bay for use by both specialists and non-specialists, including school-aged children. These keys are intended to assist in future phytoplankton studies and scientific education for students and the general public.

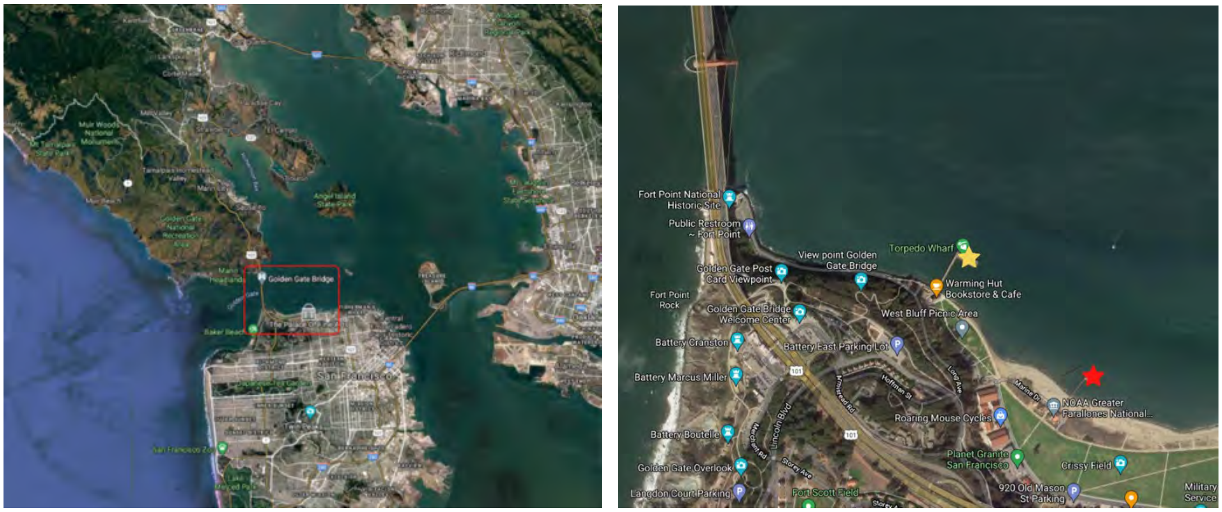
METHODS

Original project prior to the COVID-19 pandemic

As previously mentioned, Keith (2018) studied changes in phytoplankton species diversity from 2015 - 2017, observing seasonal patterns in species richness and the effect of environmental factors on species succession. Keith (2018) found an abundance of centric diatoms, accounting for >50% of the cells counted on seven sampling dates and present in all samples; however, the majority of observed centric taxa could not be identified with light microscopy (LM). Prior to the COVID-19 pandemic, this project was intended to identify individual centric diatom species in San Francisco Bay primarily from the field collections of Keith (2018) and clonal cultures maintained at USF. Scanning electron microscopy (SEM) was used to examine phenotypic characteristics of cells at higher magnifications and with a more detailed view of morphological characteristics of the diatom cells compared to LM. The SEM project was started, but due to the COVID-19 pandemic which caused temporary sampling site closures and limited access to laboratories, the project was revised to be done remotely in accordance with stay-at-home orders.

Sample collection, processing, and examination

Phytoplankton samples from the University of San Francisco used for this project were collected by Keith (2018) with a 64 µm mesh plankton net in San Francisco Bay at Torpedo Wharf and the Gulf of the Farallones Visitor Center in San Francisco, California (**Figure 4**) (NOAA 2017).



A B

Figure 4. Sampling locations. **(A)** San Francisco Bay. **(B)** Torpedo Wharf (yellow) and Gulf of the Farallones Visitor Center (NOAA) (red) in San Francisco, California, USA (Google Maps 2021).

Keith (2018) preserved the field samples in 50% ethanol and then quantified taxa under LM. She was unable to distinguish many centric diatom species under LM and grouped them as "centrics." The intended purpose of the current study (R.Laxa) was to use SEM for a more detailed view of the cells at higher magnification to identify to the species level. For this purpose, the samples were rinsed in deionized water and then treated with hot nitric/sulfuric acid to remove the organic material in preparation for examination under SEM (Battarbee 1986). Since the frustules (walls) of diatoms are made of silica, these remained intact and cleared of cell debris. The acid treatment also results in the separation of the valves, allowing the inner side of the valve to be viewed (Battarbee 1986). To prepare samples for analysis under SEM, black circular carbon conductive tabs were adhered to metal SEM stubs. A micropipette was used to add several drops of the preserved and cleaned field samples, enough to cover the carbon conductive tab. The stub was then left to air dry before being viewed under a dissecting scope to check for an adequate concentration of cells on the stub. If few cells were visible, additional drops of the preserved and treated field samples were added. The stubs were viewed under the Hitachi TM3030 SEM at USF and images of centric diatoms were taken for further analysis and identification of species.

Modifications due to the COVID-19 pandemic

Due to the COVID-19 pandemic, this project had to be modified to be done remotely in accordance with stay-at-home orders and due to limited access to laboratories and sampling sites. While the original project was intended to use SEM to identify centric diatom species that could not be discriminated under LM, the modified project aimed to develop two dichotomous taxonomic keys for planktonic diatoms in San Francisco Bay as a service to future students and the general public to assist in phytoplankton research and scientific education. One key, considered the technical key, is intended for use by an audience familiar with phytoplankton research. The other key, considered the basic key, is intended for an audience with little to no knowledge of phytoplankton terminology and research, and it is ideal as a supplemental educational tool for school-aged children.

Criteria for species inclusion in the dichotomous taxonomic keys

Before constructing the dichotomous taxonomic keys, common genera and species were considered for inclusion. Genera and species that were identified in San Francisco Bay from samples taken by the University of San Francisco since 2015 were selected (Keith 2018). Genera and species were determined to be the most well-represented and significant if they were observed in ≥50% of the samples in the study by Keith (2018) in San Francisco Bay from September 2015 - December 2017. Additional species were included if they frequently appeared in San Francisco Bay based on the USGS list of Phytoplankton in San Francisco Bay from 1992 - 2014 (Nejad et al. 2017). For the technical key, 82 diatom taxa were selected (**Table 1**).

Table 1. List of San Francisco Bay diatom species with synonyms included in “A Technical Key to Common Planktonic Diatoms in San Francisco Bay” (**Appendix B**).

Species	**Synonym**
Achnanthes sp. Bory	
Actinoptychus senarius Ehrenberg	*Actinoptychus undulatus* (Bailey) Ralfs
Actinoptychus sp. Ehrenberg	
Amphiprora sp. Ehrenberg	
Arachnoidiscus ornatus Ehrenberg	
Asterionella formosa Hassall	
Asterionella japonica Cleve	*Asterionellopsis glacialis* (Castracane) Round
Asterolampra sp. Ehrenberg	
Asteromphalus Ehrenberg	
Asteromphalus hookeri Ehrenberg	*Asteromphalus humboldtii* Ehrenberg
Bacillaria paxillifer (Müller) Marsson	*Bacillaria paradoxa* Gmelin *Nitzschia paradoxa* (Gmelin) Grunow *Vibrio paxillifer* Müller
Biddulphia sp. Gray	
Chaetoceros affinis Lauder	*Chaetoceros affine* Lauder *Chaetoceros schuttii* Cleve
Chaetoceros constrictus Gran	
Chaetoceros curvisetus Cleve	
Chaetoceros debilis Cleve	*Chaetoceros debile* Cleve

Table 1. List of San Francisco Bay diatom species with synonyms included in "A Technical Key to Common Planktonic Diatoms in San Francisco Bay" (**Appendix B**).

Species	Synonym
Chaetoceros decipiens Cleve	
Chaetoceros didymus Ehrenberg	*Chaetoceros didymum* Ehrenberg
Chaetoceros radicans Schütt	
Chaetoceros socialis Lauder	
Chaetoceros spp. Ehrenberg	
Chaetoceros tortissimus Gran	
Corethron hystrix Hensen	*Corethron criophilum var. histrix* (Hensen) Hendey
Corethron pennatum (Grunow) Ostenfeld	
Corethron sp. Castracane	
Coscinodiscus angustelineatus Schmidt	*Thalassiosira anguste-lineata* (Schmidt) Fryxell and Hasle
Coscinodiscus curvatulus var. curvatulus Grunow	*Actinocyclus curvatulus* (Grunow) Cleve
Coscinodiscus lentiginosus var. lentiginosus Janisch	*Thalassiosira lentiginosa* (Janisch) Fryxell
Coscinodiscus oculus-iridis Ehrenberg	
Coscinodiscus spp. Ehrenberg	
Detonula sp. Schütt ex De Toni	
Ditylum brightwellii (West) Grunow	*Triceratium brightwellii* West
Ditylum sp. Bailey ex Bailey	
Eucampia sp. Ehrenberg	
Eucampia striata Stolterfoth	*Guinardia striata* (Stolterfoth) Hasle *Rhizosolenia stolterfothii* Peragallo
Eucampia zodiacus Ehrenberg	
Gyrosigma balticum (Ehrenberg) Rabenhorst	*Pleurosigma balticum* (Ehrenberg) Smith
Heliotheca sp. Ricard	*Streptotheca* sp. Shrubsole
Heliotheca tamesis (Shrubsole) Ricard	*Streptotheca thamensis* Shrubsole
Hobaniella longicruris (Greville) Sims and Williams	*Odontella longicruris* (Greville) Hoban *Biddulphia longicruris var. longicruris* Greville
Isthmia nervosa Kützing	
Lauderia confervacea Cleve	*Detonula confervacea* (Cleve) Gran
Lauderia sp. Cleve	
Leptocylindrus danicus Cleve	
Lithodesmium undulatum Ehrenberg	
Melosira arctica var. arctica Dickie	*Melosira arctica* (Ehrenberg) Ralfs *Gaillonella arctica* (Dickie) Ehrenberg
Melosira moniliformis (Müller) Agardh	
Melosira sp. Agardh	
Melosira varians Agardh	
Navicula challengeri Grunow	*Tropidoneis antarctica* (Grunow) Cleve *Membraneis challengeri* (Grunow) Paddock *Amphiprora challengeri* (Grunow) De Toni
Navicula sp. Bory de Saint-Vincent	
Nitzschia closterium (Ehrenberg) Smith	*Cylindrotheca closterium* (Ehrenberg) Lewin and Reimann *Phaeodactylum tricornutum* Bohlin
Nitzschia longissima (Brébisson) Ralfs	*Nitzschiella longissima* (Brébisson) Rabenhorst

Table 1. List of San Francisco Bay diatom species with synonyms included in “A Technical Key to Common Planktonic Diatoms in San Francisco Bay” (**Appendix B**).

Species	Synonym
Nitzschia sigma (Kützing) Smith	*Sigmatella sigma* (Kützing) Frenguelli
Nitzschia sp. Hassall	
Odontella aurita (Lyngbye) Agardh	*Biddulphia aurita* (Lyngbye) Brébisson
Odontella obtusa Kützing	*Biddulphia aurita var. obtusa* (Kützing) Hustedt
Paralia sulcata (Ehrenberg) Cleve	*Melosira sulcata* (Ehrenberg) Kützing *Gaillionella sulcata* Ehrenberg *Orthoseira marina* Smith
Pleurosgima spp. Smith	
Porosira sp. Jorgensen	
Pseudo-nitzschia sp. Peragallo	
Rhizosolenia calcar-avis Schultze	*Pseudosolenia calcar-avis* (Schultze) Sundström
Rhizosolenia robusta Norman ex Ralfs	
Rhizosolenia semispina Hensen	*Rhizosolenia hebetata* (Hensen) Margalef *Rhizosolenia hebetata f. semispina* (Hensen) Gran
Rhizosolenia setigera Brightwell	
Rhizosolenia sp. Brightwell	*Proboscia* sp. Sundstrom
Rhizosolenia styliformis Brightwell	
Skeletonema costatum (Greville) Cleve	
Skeletonema sp. Greville	
Stephanopyxis sp. Ehrenberg	
Stephanopyxis turris (Greville) Ralfs	
Synedra nitzschioides f. nitzschioides Grunow	*Thalassionema nitzschioides* (Grunow) Mereschkowsky *Thalassiothrix nitzschioides* Grunow
Thalassiosira nordenskioeldii Cleve	
Thalassiosira rotula Meunier	*Coscinodiscus rotulus* (Meunier) Cleve-Euler
Thalassiosira spp. Cleve	
Thalassiosira subtilis (Ostenfeld) Gran	
Thalassiothrix mediterranea var. pacifica Cupp	*Lioloma pacificum* (Cupp) Hasle
Thalassiothrix sp. Cleve and Grunow	
Triceratium alternans Bailey	*Trigonium alternans* (Bailey) Mann *Biddulphia alternans* (Bailey) Van Heurck
Triceratium sp. Ehrenberg	
Trieres mobiliensis (Bailey) Ashworth and Theriot	*Biddulphia mobiliensis* (Bailey) Grunow *Odontella weissflogii* Grunow
Tropidoneis sp. Cleve	

Out of the 82 diatom taxa in the technical key, 41 taxa were determined to be the most significant and were selected for inclusion in the basic key. Additionally, 14 dinoflagellates were included as they are commonly seen and identifiable in San Francisco Bay (**Table 2**).

Table 2. List of phytoplankton species with synonyms in San Francisco Bay included in "A Basic Key to Common Phytoplankton in San Francisco Bay" (**Appendix C**).

Phytoplankton Type	Species	Synonym
Diatom (Centric)	*Asteromphalus* Ehrenberg	
	Chaetoceros curvisetus Cleve	
	Chaetoceros debilis Cleve	*Chaetoceros debile* Cleve
	Chaetoceros decipiens Cleve	
	Chaetoceros didymus Ehrenberg	*Chaetoceros didymum* Ehrenberg
	Chaetoceros socialis Lauder	
	Corethron pennatum (Grunow) Ostenfeld	
	Coscinodiscus oculus-iridis Ehrenberg	
	Ditylum brightwellii (West) Grunow	*Triceratium brightwellii* West
	Eucampia striata Stolterfoth	*Guinardia striata* (Stolterfoth) Hasle *Rhizosolenia stolterfothii Peragallo*
	Eucampia zodiacus Ehrenberg	
	Hobaniella longicruris (Greville) Sims and Williams	*Odontella longicruris* (Greville) Hoban *Biddulphia longicruris var. longicruris* Greville
	Isthmia nervosa Kützing	
	Lauderia confervacea Cleve	*Detonula confervacea* (Cleve) Gran
	Lauderia sp. Cleve	
	Leptocylindrus danicus Cleve	
	Lithodesmium undulatum Ehrenberg	
	Melosira moniliformis (Müller) Agard	
	Odontella aurita (Lyngbye) Agardh	*Biddulphia aurita* (Lyngbye) Brébisson
	Paralia sulcata (Ehrenberg) Cleve	*Melosira sulcata* (Ehrenberg) Kützing *Gaillionella sulcata* Ehrenberg *Orthoseira marina* Smith
	Porosira sp. Jorgensen	
	Rhizosolenia semispina Hensen	*Rhizosolenia hebetata* (Hensen) Margalef *Rhizosolenia hebetata f. semispina* (Hensen) Gran
	Skeletonema costatum (Greville) Cleve	
	Stephanopyxis turris (Greville) Ralfs	
	Heliotheca tamesis (Shrubsole) Ricard	*Streptotheca thamensis* Shrubsole
	Thalassiosira nordenskioeldii Cleve	
	Thalassiosira subtilis (Ostenfeld) Gran	
	Triceratium sp. Ehrenberg	
	Trieres mobiliensis (Bailey) Ashworth and Theriot	*Biddulphia mobiliensis* (Bailey) Grunow *Odontella weissflogii* Grunow
Diatom (Pennate)	*Amphiprora* sp. Ehrenberg	
	Asterionella japonica Cleve	*Asterionellopsis glacialis* (Castracane) Round

Table 2. List of phytoplankton species with synonyms in San Francisco Bay included in "A Basic Key to Common Phytoplankton in San Francisco Bay" (**Appendix C**).

Phytoplankton Type	Species	Synonym
Diatom (Pennate)	*Bacillaria paxillifer* (Müller) Marsson	*Bacillaria paradoxa* Gmelin *Nitzschia paradoxa* (Gmelin) Grunow *Vibrio paxillifer* Müller
	Navicula challengeri Grunow	*Tropidoneis antarctica* (Grunow) Cleve *Membraneis challengeri* (Grunow) Paddock *Amphiprora challengeri* (Grunow) De Toni
	Navicula sp. Bory de Saint-Vincent	
	Nitzschia closterium (Ehrenberg) W. Smith	*Cylindrotheca closterium* (Ehrenberg) Lewin and Reimann *Phaeodactylum tricornutum* Bohlin
	Nitzschia longissima (Brébisson) Ralfs	*Nitzschiella longissima* (Brébisson) Rabenhorst
	Nitzschia sp. Hassall	
	Pleurosigma spp. W. Smith	
	Pseudo-nitzschia sp. Peragallo	
	Synedra nitzschioides f. nitzschioides Grunow	*Thalassionema nitzschioides* (Grunow) Mereschkowsky *Thalassiothrix nitzschioides* Grunow
	Thalassiothrix sp. Cleve and Grunow	
Dinoflagellate	*Dinophysis* sp.	
	Gonyaulax sp.	
	Gymnodinium sp.	
	Noctiluca scintillans (Macartney) Kofoid & Swezy	
	Peridinium spp.	
	Polykrikos kofoidii Chatton	
	Prorocentrum sp.	
	Protoperidinium sp.	
	Pyrocystis lunula (Schütt) Schütt	
	Tripos furca (Ehrenberg) Gómez	*Ceratium furca* (Ehrenberg) Claparède & Lachmann
	Tripos fusus (Ehrenberg) Gómez	*Ceratium fusus* (Ehrenberg) Dujardin
	Tripos gibberus (Gourret) Gómez	*Ceratium gibberum* Gourret
	Tripos lineatus (Ehrenberg) Gómez	*Ceratium lineatum* (Ehrenberg) Cleve *Peridinium lineatum* Ehrenberg
	Tripos muelleri Bory	*Ceratium tripos* (Müller) Nitzsch

Construction of dichotomous taxonomic keys

After the list of species was generated, a series of resources were consulted to construct the dichotomous taxonomic keys, including Boyer (1927), Cupp (1943), Keith (2018), Smith and West (1853), and Tomas et al. (1997) (see also **Appendix A**). A dichotomous decision tree framework was used to visually clarify how species were related taxonomically. The principle of parsimony was implemented to simplify the number of steps needed to differentiate genera and species from one another. Although previous research showed that a random decision forest framework could produce better recognition rates than single decision trees, this current project (R.Laxa) used the dichotomous decision tree framework in an effort to simplify the species identification process (Fischer and Bunke 2001). Two keys were constructed in this project: “A Technical Key to Common Planktonic Diatoms in San Francisco Bay” (**Appendix B**) and "A Basic Key to Common Phytoplankton in San Francisco Bay" (**Appendix C**). Software including Visual Paradigm Online Free Edition (https://online.visual-paradigm.com/), Adobe Acrobat DC, and Microsoft PowerPoint were used to construct the keys.

“A Technical Key to Common Planktonic Diatoms in San Francisco Bay” (**Appendix B**) included the most common species of diatoms found in San Francisco Bay (**Table 1**) and organized them in dichotomous decision trees based on taxonomy. The technical key was constructed using Visual Paradigm Online Free Edition (https://online.visual-paradigm.com/) with the “Dichotomous Key” format to build the taxonomic decision trees as the software could accommodate for how spread out the trees could become. Additionally, the key was edited using Adobe Acrobat DC to make it digitally interactive, allowing for easier navigation.

Literature by Tomas et al. (1997) was primarily referenced to set up the keys through the taxonomic classification system of order, suborder, family, genus, species. The key starts by looking at the symmetry of the diatom (whether radially symmetric around a point or bilaterally symmetric) then splits off to order Biddulphiales (centric diatoms) and order Bacillariales (pennate diatoms), directing to different pages specific to the order of interest. These pages include detailed morphological descriptions of suborders and families and further directs to different pages specific to the family of interest (**Figure 5**). From there, the key asks a series of questions regarding morphology observable with LM and SEM through the dichotomous decision tree framework.

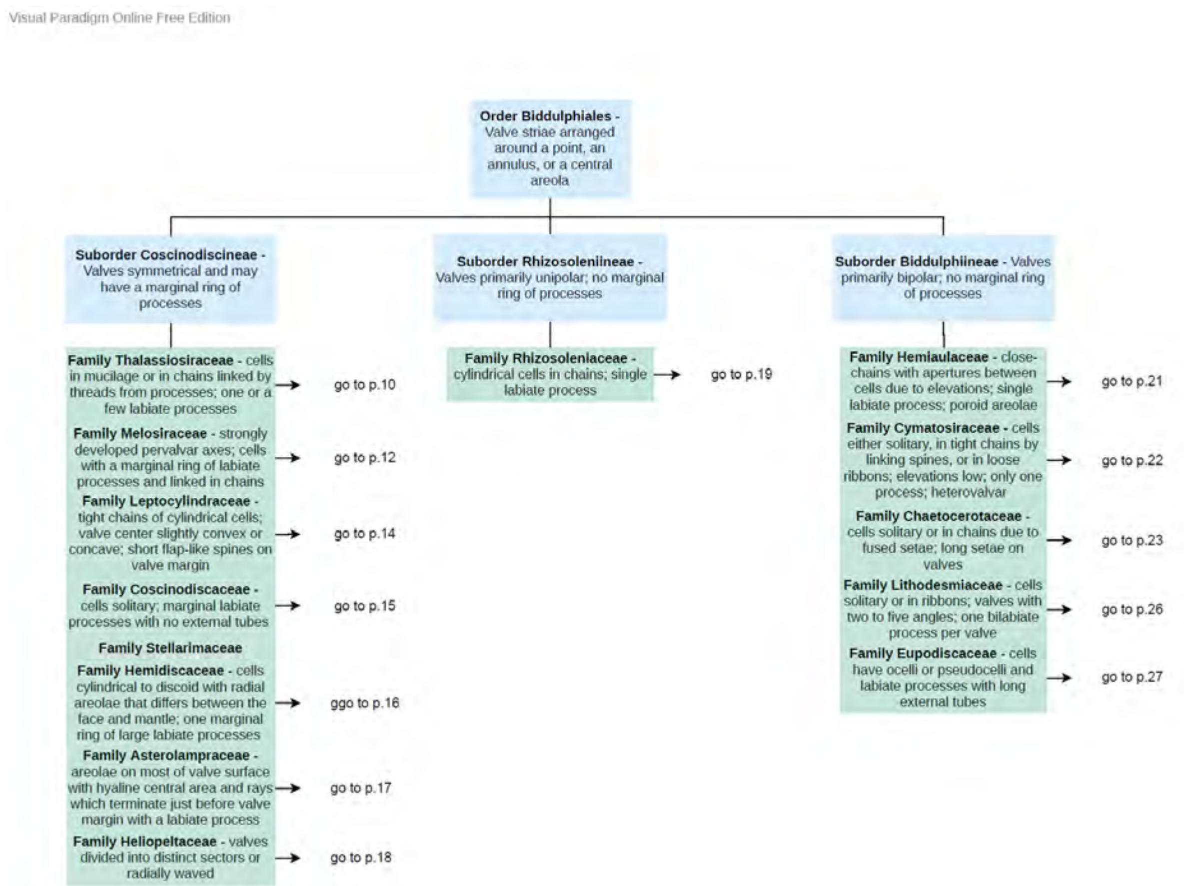


Figure 5. Page 7 from “A Technical Key to Common Planktonic Diatoms in San Francisco Bay” (**Appendix B**), showing order Biddulphiales; suborders Coscinodiscineae, Rhizosoleniineae, and Biddulphiineae; and families corresponding to each suborder with detailed morphological descriptions and directions to pages in the key for further discrimination to the genus and species level.

Phytoplankton terminology used throughout the key is defined towards the end of the key to assist the reader through distinguishing the diatom down to the genus or species level. Size ranges for the species were also included in the key since diatom cell division results in variable sizes, as discussed previously (Figure 3). Taxonomic levels were color-coded: Blue boxes in the technical key indicate order and suborder, green boxes indicate family, red boxes indicate genus, and orange boxes indicate species. Purple boxes indicate genera based on Cupp (1943) and Boyer (1927) which classified Bacillariophyceae into two sections that differ from Tomas et al. (1997) - Centricae (Centric Diatoms) and Pennatae (Pennate Diatoms) - then subsections, subfamilies, tribes, genera, and then species.

"A Basic Key to Common Phytoplankton in San Francisco Bay" (**Appendix C**) included the most well-represented and significant genera and species of diatoms, as well as some dinoflagellates that are common taxa seen in San Francisco Bay. Unlike the technical key, the basic key organized the phytoplankton in dichotomous decision trees based on morphology observable under the LM rather than phylogenic relationships to identify the phytoplankton. Therefore, the key did not go through order, suborder, family, genus, and species but rather starts by looking at whether the phytoplankton of interest is found solitary, associated in a cluster, or united in a chain. From there, the key asks a series of questions to guide the reader through distinguishing the cell down to the genus or species level. Since the basic key is organized based on physical characteristics regardless of taxonomy, a color code is used to indicate whether a genus or species is a centric diatom (green), pennate diatom (purple), or dinoflagellate (orange) and a taxonomic species list is included at the end of the key as it is important to recognize where the phytoplankton fit taxonomically beyond being able to identify them on a genus or species level. The basic key was constructed using Microsoft PowerPoint rather than Visual Paradigm Online Free Edition since Microsoft PowerPoint allowed for imagery of phytoplankton to be easily implemented since the dichotomous decision trees in the basic key is more simplified compared to those in the technical key and could include imagery within the trees.

For both keys, DiatomBase (2021) was primarily used to determine the current accepted taxon name and synonyms of diatom species. Additionally, AlgaeBase (2021) was used in the basic key to determine the current accepted taxon name and synonyms of dinoflagellate species. Both keys also include images of the species. The technical key includes both LM and SEM images. However, most of the general public do not have access to SEM, so the basic key includes only LM images. Unless otherwise indicated, all LM images were taken by Dr. Deneb Karentz from the University of San Francisco.

RESULTS AND PRODUCTS

The original project, prior to the COVID-19 pandemic, was to use SEM to examine phenotypic characteristics of diatom cells and clarify the taxonomy of the assemblage of diatoms referred to as “centrics” from the study by Keith (2018). From the analysis of SEM images, five centric diatom species were identified: *Coscinodiscus curvatulus* (**Figure 6**), *Actinoptychus senarius* (**Figure 7**), *Coscinodiscus oculus-iridis* (**Figure 8**), *Coscinodiscus lentiginosa* (**Figure 9**), and *Thalassiosira nordenskioeldii* (**Figure 10**).

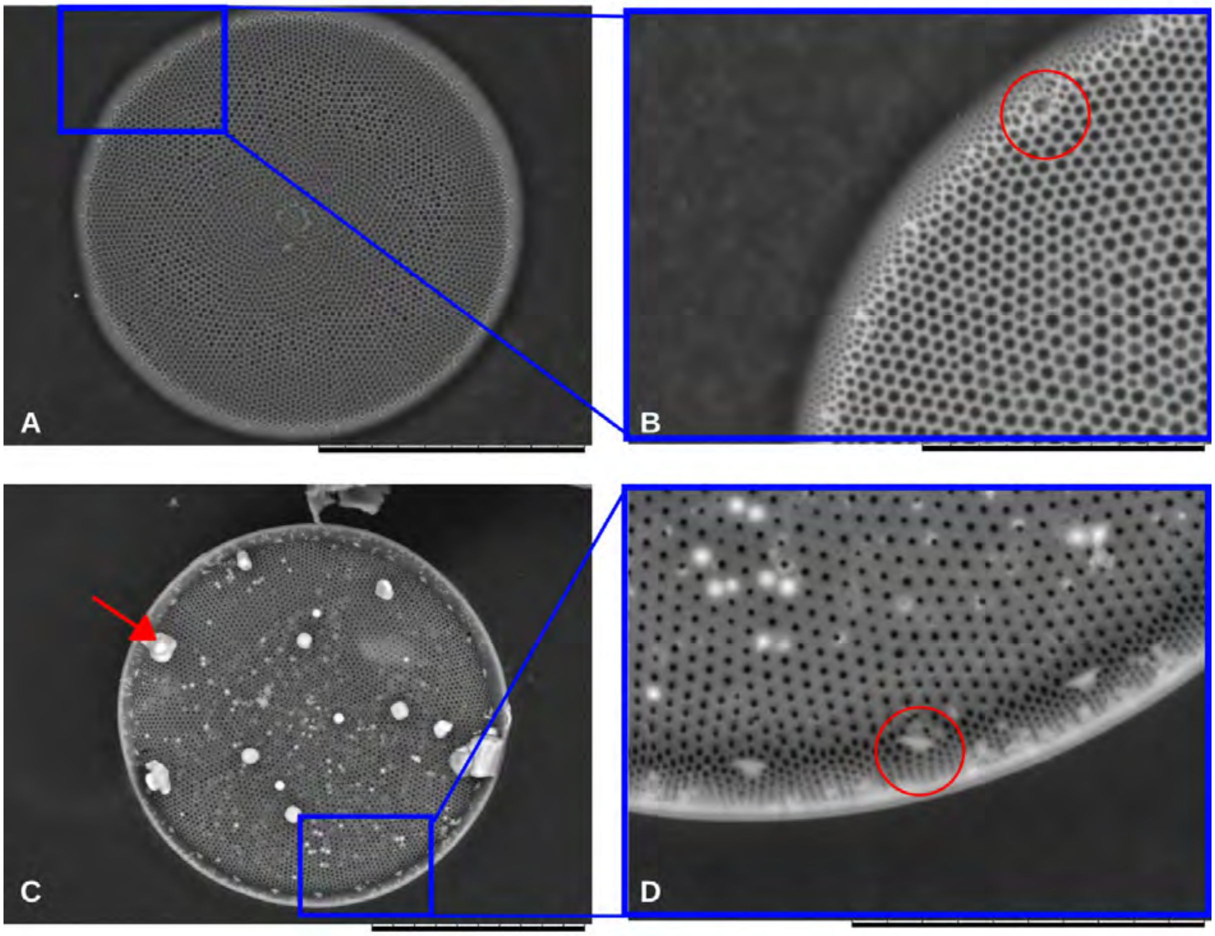


Figure 6. SEM images of *Coscinodiscus curvatulus.* **(A)** external valve face is concave (margins more raised than the center) and shows radial areolae of equal-sized pores which are divided into triangular sections extending from the center (x1.5k, 50 µm scale). **(B)** higher magnification of **A** shows pseudonodulus (circled) slightly away from the marginal band (x4.0k, 20 µm scale). **(C)** internal valve face with sand grains (arrow) shows evenly spaced labiate processes on the wall of the valve (~10 µm apart) (x1.2k, 50 µm scale). **(D)** higher magnification of **C** shows labiate processes (circled) and that areolae persist on valve walls (x5.0k, 20 µm scale).

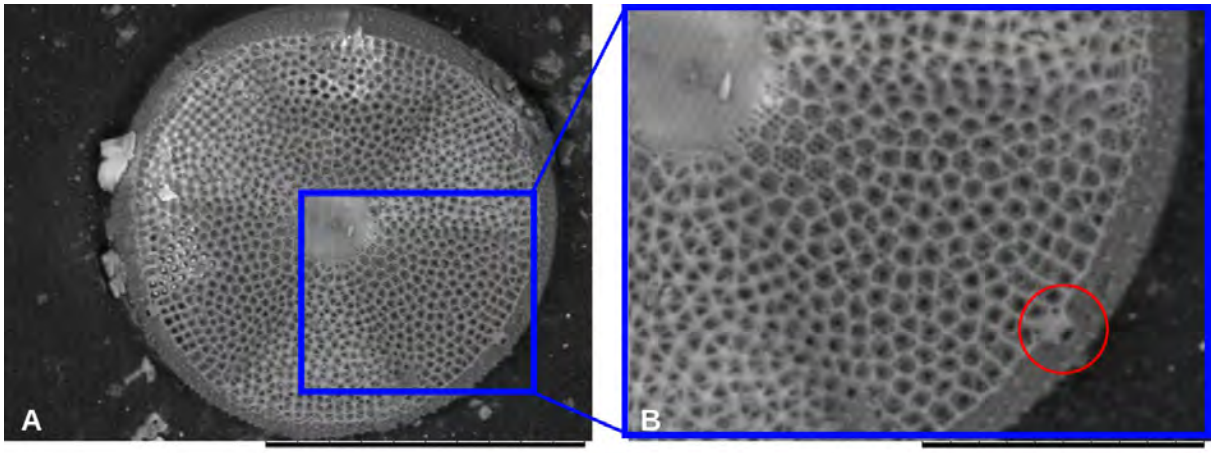


Figure 7. SEM images of *Actinoptychus senarius.* **(A)** external valve face shows six alternately raised and depressed sectors, smooth central area, and a beveled edge (x1.8k, 50 µm scale). **(B)** higher magnification of **A** shows strongly areolated outer membrane, less areolated inner membrane, one marginal pore-like process (circled), and numerous marginal spinulae (x4.0k, 20 µm scale).

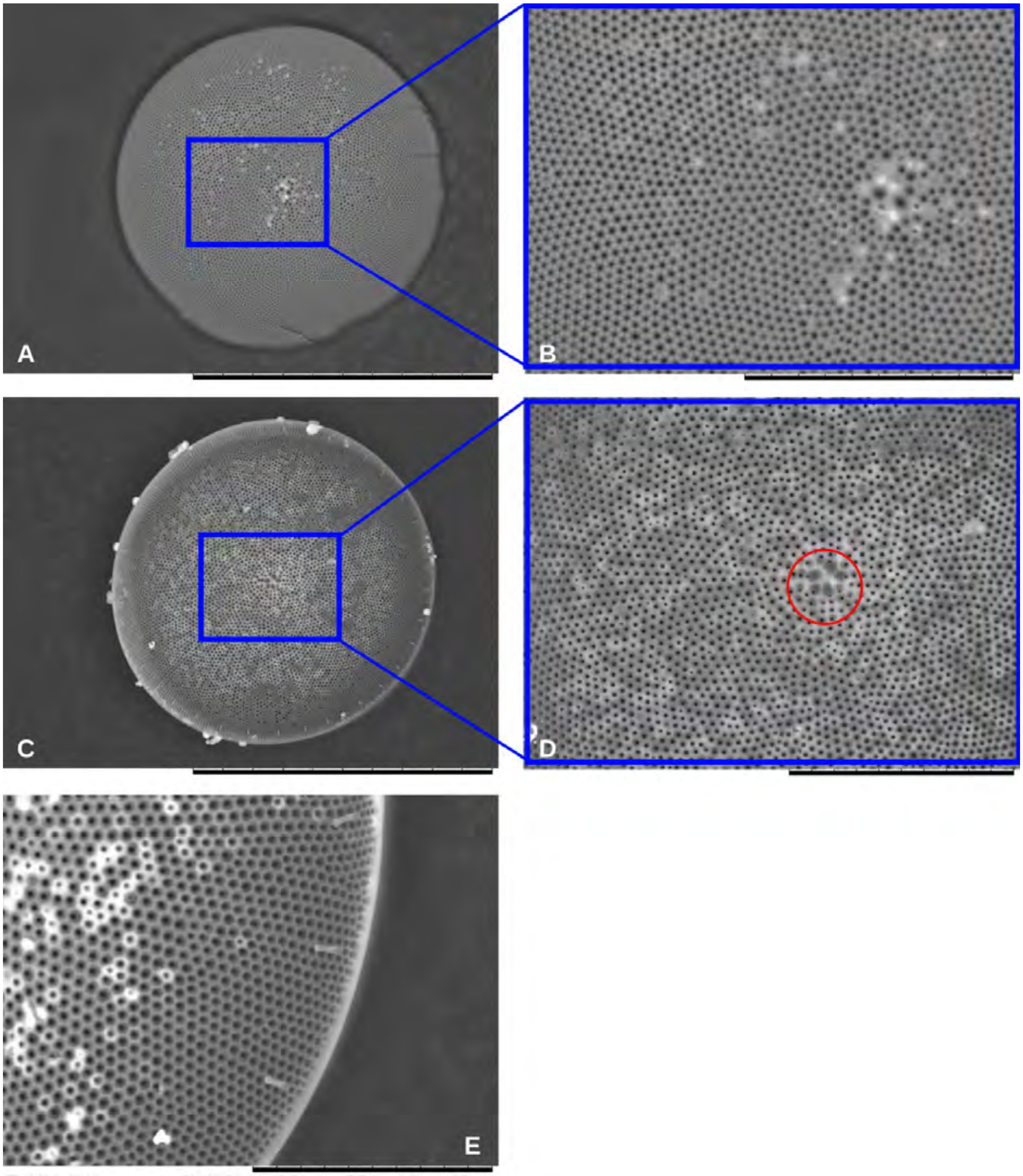


Figure 8. SEM images of *Coscinodiscus oculus-iridis.* **(A)** external valve face (x1.0k, 100 µm scale). **(B)** higher magnification of **A** shows “flower configuration” of pores only visible in external valve view (x3.0k, 30 µm scale). **(C)** internal valve face shows radial areolae and small circular pores (x1.0k, 100 µm scale). **(D)** higher magnification view of **C** shows central rosette (circled) (x2.5k, 30 µm scale). **(E)** marginal tube-like processes (range from ~7-10 µm apart) only visible in internal valve view (x4.0k, 20 µm scale).

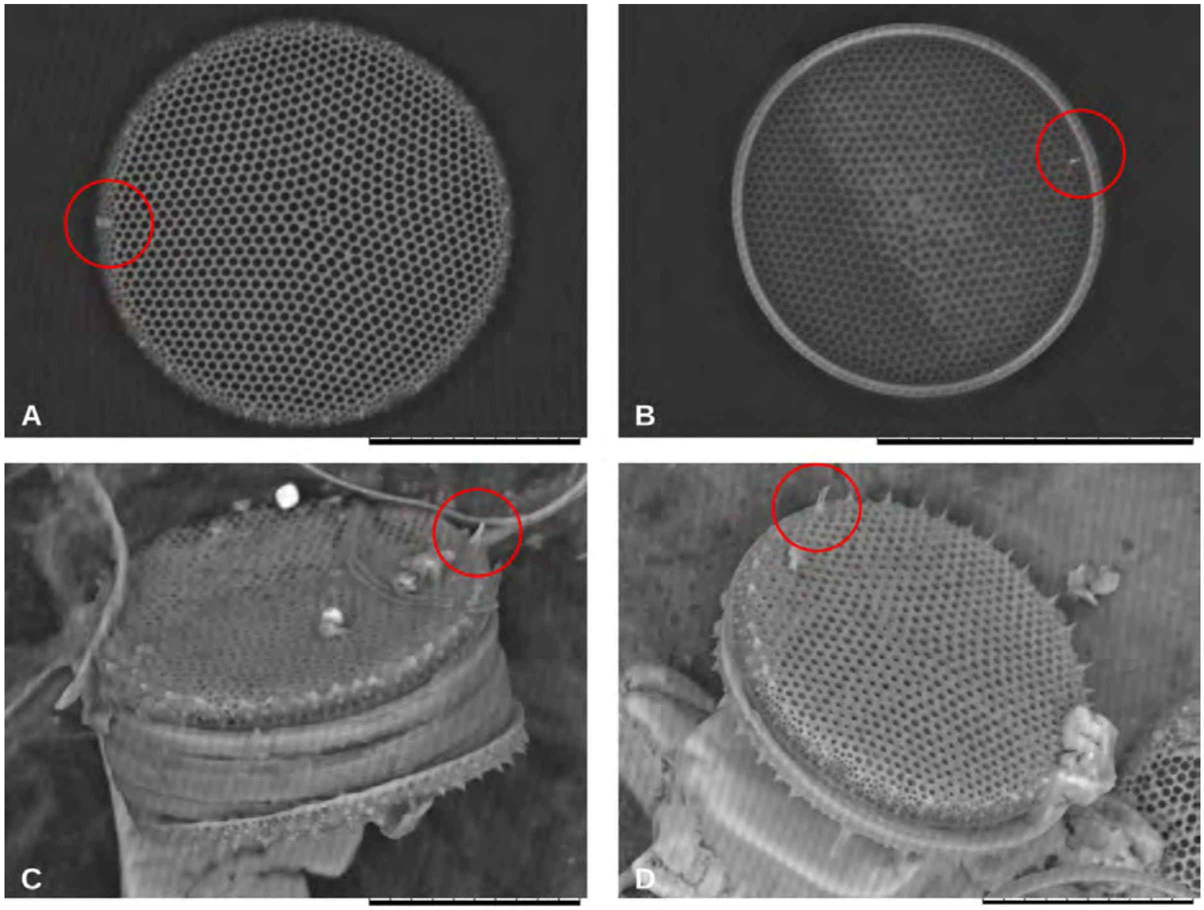


Figure 9. SEM images of *Coscinodiscus lentiginosa*, labiate process (circled) **(A)** external valve face shows a slightly beveled edge (x6.0k, 10 µm scale). **(B)** internal valve face shows hexagonal areolae (x1.8k, 50 µm scale). **(C)** full cell with girdle bands (x2.0k, 30 µm scale). **(D)** full cell shows spines at the upper edge of the bevel (x2.0k, 30 µm scale).

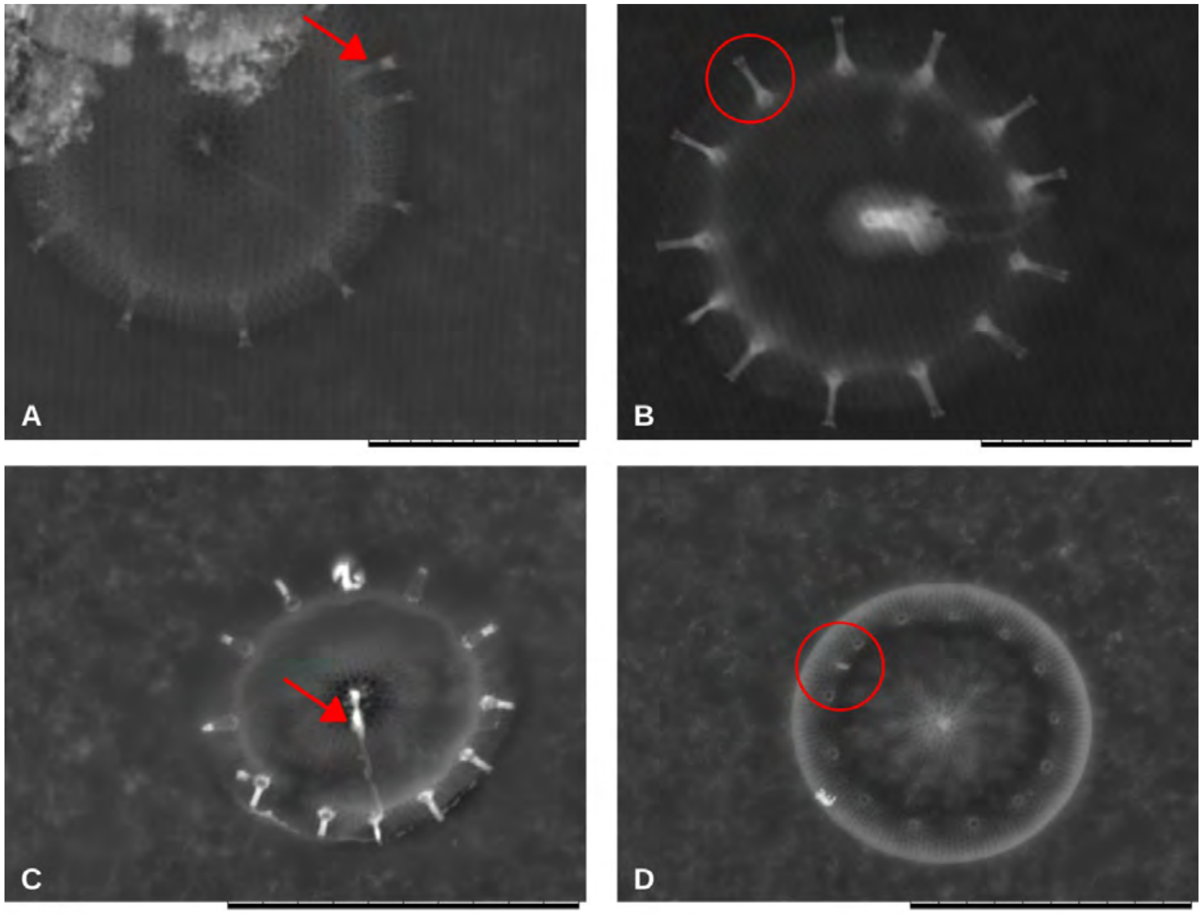


Figure 10. SEM images of *Thalassiosira nordenskioeldii.* **(A)** external valve face shows labiate process (arrow) and beveled edge (x6.0k, 10 µm scale). **(B)** external valve face shows strutted processes (circled) (x6.0k, 10 µm scale). **(C)** external valve face shows central process with filamentous structure attached (arrow) (x5.0k, 20 µm scale). **(D)** internal valve face shows linear, uniform areolae and labiate process (circled) (x4.0k, 20 µm scale).

The revised project constructed two dichotomous taxonomic keys for San Francisco Bay planktonic diatoms (**Appendix B and C**). “A Technical Key to Common Planktonic Diatoms in San Francisco Bay” (**Appendix B**) is intended for an audience that is more familiar with phytoplankton terminology and research since the key goes into detailed taxonomic classification and morphological descriptions. The technical key includes the most common species of diatoms found in San Francisco Bay (**Table 1, Appendix A**). “A Basic Key to Common Phytoplankton in San Francisco Bay” (**Appendix C**) is a more simplified version that is intended for an audience that is new to or does not have a basic knowledge of phytoplankton terminology and research. It is suitable for school-aged children and is organized based on morphology observable under LM rather than by classical taxonomy, although a taxonomic species list is included at the end of the key to inform where the species fit in phytoplankton taxonomy. Dinoflagellates were added to the Basic Key since there are some common taxa seen in San Francisco Bay. Additionally, a collection of open-source phytoplankton taxonomy websites was compiled throughout the project (**Appendix D**). These keys, in addition to the open-source websites, will aid in the taxonomic identification of phytoplankton species found in San Francisco Bay.

DISCUSSION

Significant diatom species in San Francisco Bay

The most well-represented genera and significant diatom species found in San Francisco Bay, based on if they were observed in ≥50% of the samples in the study by Keith (2018) from September 2015 - December 2017, included *Chaetoceros* spp*., Ditylum brightwelli, Pseudo-nitzschia* spp., *Rhizosolenia setigera, Skeletonema costatum, Thalassiosira* spp. and *Trieres mobiliensis*.

***Chaetoceros* Species**

Bacillariophyceae (Class)
    Biddulphiales (Order)
        Biddulphiineae (Suborder)
            Chaetocerotaceae (Family)
                Chaetoceros (Genus)
(Tomas et al. 1997)

The genus *Chaetoceros* has ~400 species (Tomas et al. 1997). Although this number has varied over time as the validity of some species have been questioned, *Chaetoceros* is still one of the largest marine phytoplankton genera and one of the largest groups of centric diatoms (Cupp 1943, Malviya et al. 2016, Tomas et al. 1997). It is divided into two subgenera - *Phaeoceros* and *Hyalochaete* - and is characterized by cells that are mostly elliptical and rarely circular in valve view, rectangular in girdle view, and have setae or hollow extensions that appear as elongated spines which can connect the setae of neighboring cells (Cupp 1943, Tomas et al. 1997). These setae allow *Chaetoceros* species to float and stay in the euphotic zone (Perry 2003). Species within this genus vary by characteristics of the chloroplasts (such as their presence in setae, number, shape, and size), setae morphology, girdle height, chain direction (whether straight, curved/helical, or twisted), and resting spores (**Figure 11A**) (Tomas et al. 1997). While some species are oceanic, the majority of *Chaetoceros* species are neritic. *Chaetoceros curvisetus* and *Chaetoceros decipiens* were the two species that appeared in ≥50% of the samples by Keith (2018).

C. curvisetus is usually found as a spirally curved chain of cells with setae that are directed outwards from the spiral (**Figure 11B**) (Cupp 1943, Tomas et al. 1997). The cells are 20-38 μm tall (pervalvar axis) and the concave valves are 7-30 μm in diameter and connect to one another via elevations at the cell margin (Cupp 1943, Scott and Marchant 2005, Tomas et al. 1997). Under LM, apertures, or openings between the valves, can be seen. SEM may be required to see the short central labiate process that is flattened and hidden in the inner valve view (Scott and Marchant 2005, Simonsen 1975, Tomas et al. 1997). *C. curvisetus* is a neritic, cosmopolitan, and mostly south temperate and warm water species (Cupp 1943, Scott and Marchant 2005). It is often found off California, particularly in the spring and fall (**Figure 11D**) (Cupp 1943).

C. decipiens cells are 12-78 µm in diameter and have four sharp elevated corners in girdle view that touch the corners of adjacent cells to form a straight chain and do not have resting spores (**Figure 11C**). The setae begin fused in pairs at the base for a length that is two to three times larger than the diameter of the setae before separating (Cupp 1943, Tomas et al. 1997). Terminal setae, or setae present on the end cells of the chain, are shorter and thicker (Simonsen 1975, Tomas et al. 1997). Similar to *C. curvisetus*, *C. decipiens* has apertures that vary in shape, however, the type of shape changes according to the season; in particular, apertures tend to be smaller and more linear to lanceolate during the winter whereas they tend to be larger and more elliptical to circular during the summer and fall (Cupp 1943). Under SEM, a central labiate process is visible in the inner valve view (Tomas et al. 1997). *C. decipiens* is oceanic, arctic, and boreal (**Figure 11D**) (Boyer 1927, Cupp 1943, Ocean Biodiversity Observation System 2021).

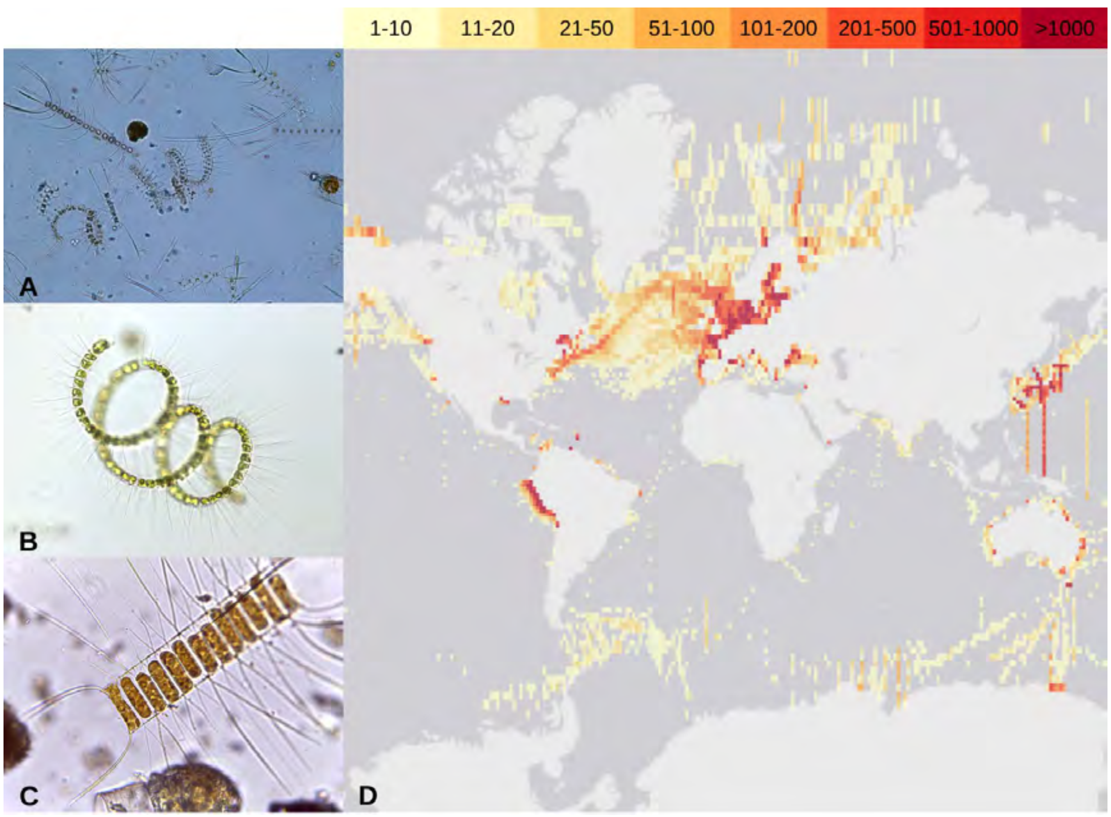


Figure 11. *Chaetoceros species.* **(A)** LM image of *Chaetoceros* species. **(B)** LM image of *Chaetoceros curvisetus* (LM image by Stephanie Anderson). **(C)** LM image of *Chaetoceros decipiens.* **(D)** global distribution of *Chaetoceros* spp. based on Ocean Biodiversity Observation System (2021). Color scale indicates the number of records at the sampling site out of 434,817 global records.

Ditylum brightwellii

Bacillariophyceae (Class)
Biddulphiales (Order)
Biddulphiineae (Suborder)
Lithodesmiaceae (Family)
Ditylum (Genus)
Ditylum brightwellii (Species)
(Tomas et al. 1997)

Ditylum brightwellii is found as solitary cells that are usually triangular in valve view and rectangular or cylindrical in girdle view with a diameter of 14-100 µm and a height (pervalvar axis) of 80-130 µm (**Figure 12A**) (Cupp 1943, Tomas et al. 1997). Additionally, there is a hollow spine projecting from the center of the valve (Cupp 1943). Areolae on the valve face are larger than the areolae on the mantle and are elongated on the central region of the valve face (Tomas et al. 1997). One structure that is particularly characteristic of the genus *Ditylum* is the presence of a ridge on the margin of the cells. In *D. brightwellii,* this marginal ridge is either slotted, meaning that the basal membrane is perforated, or fimbriate with ansulae, meaning that it is fringed with ribbon-like structures which are split down the middle longitudinally (Tomas et al. 1997). *D. brightwellii* is a neritic, cosmopolitan and south temperate species (**Figure 12B**) (Cupp 1943, Ocean Biodiversity Observation System 2021).

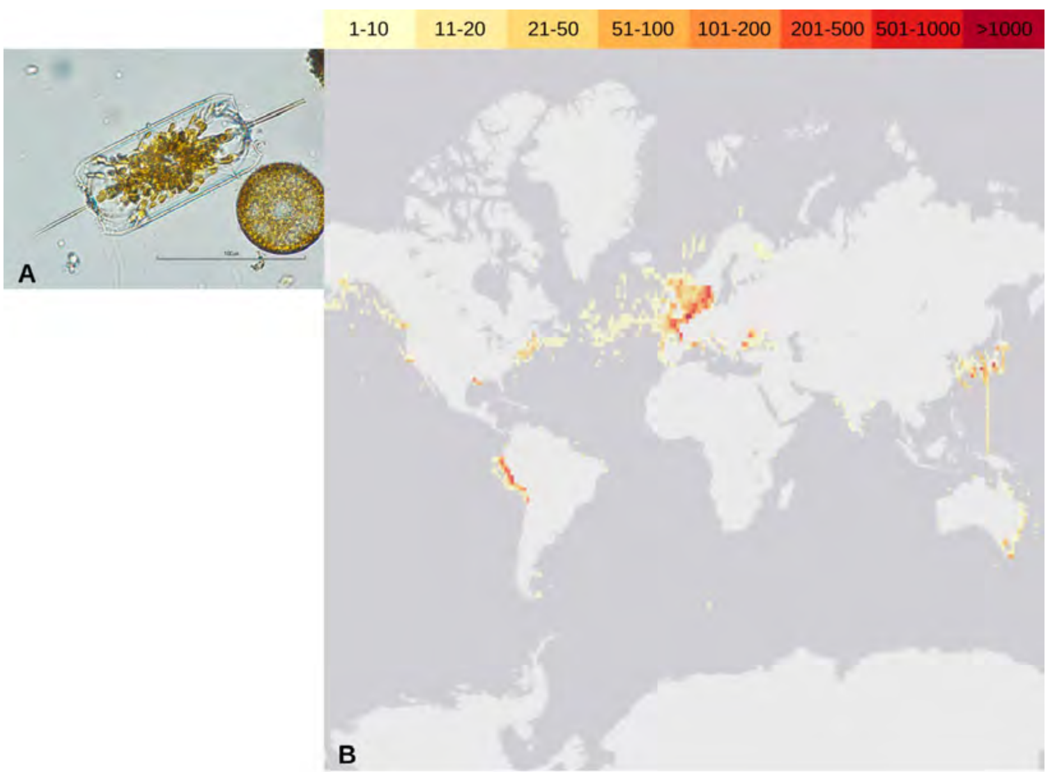


Figure 12. *Ditylum brightwellii*. **(A)** LM image of *D. brightwellii.* **(B)** global distribution of *D. brightwellii* based on Ocean Biodiversity Observation System (2021). Color scale indicates the number of records at the sampling site out of 29,905 global records.

***Pseudo-nitzschia* Species**

Bacillariophyceae (Class)
    Bacillariales (Order)
        Bacillariineae (Suborder)
            Bacillariaceae (Family)
                Pseudo-nitzschia (Genus)
(Tomas et al. 1997)

The genus *Pseudo-nitzschia* has over 50 known species and the cells are often found in chains in which the ends of the rectangular to canoe-shaped valves overlap with adjacent cells to form the chains (**Figure 13A**) (Bates et al. 2018, Tomas et al. 1997). One characteristic that makes them unique from *Nitzschia* species includes the unelevated raphe system, or slit on the valve wall, that is visible under SEM (Ross et al. 1975, Tomas et al. 1997). Another unique characteristic of *Pseudo-nitzschia* is the narrow, pointed and open intercalary bands of the valve girdle which usually have striae of poroids or areolae that are not constricted by a foramen (Ross et al. 1979, Simonsen 1975, Tomas et al. 1997). *Pseudo-nitzschia* are marine species and are distributed around the globe, particularly near temperate coasts (**Figure 13B**) (Ocean Biodiversity Observation System 2021, Tomas et al. 1997).

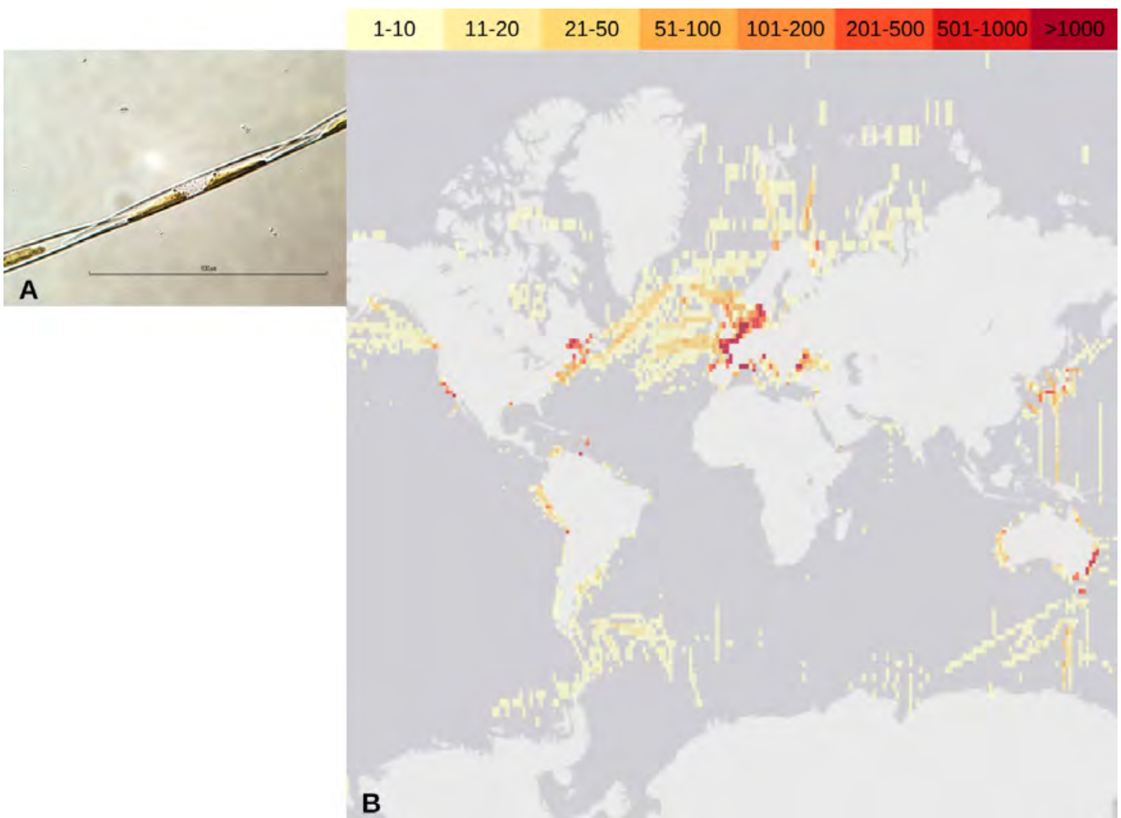


Figure 13. *Pseudo-nitzschia* species. **(A)** LM image of *Pseudo-nitzschia* species. **(B)** global distribution of *Pseudo-nitzschia* spp. based on Ocean Biodiversity Observation System (2021). Color scale indicates the number of records at the sampling site out of 144,658 global records.

What makes *Pseudo-nitzschia* particularly significant is that approximately 50% of species are toxigenic and can produce domoic acid, a neurotoxin that can accumulate in the tissues of shellfish and fish (Bates et al. 2018, Buteyko 2010, Ekstrom et al. 2020, Moore et al. 2020, Perry 2003). When birds and marine mammals, like sea lions, consume the shellfish and fish, the levels of accumulated neurotoxin cause seizures and even death (Buteyko 2010). In humans, consuming toxic shellfish and fish can result in seizures, abnormal heart rate and/or rhythm (cardiac arrhythmias), comas, and even death if the intoxication is severe enough (Ekstrom et al. 2020, Perry 2003). However, less severe intoxication levels can still result in a multitude of symptoms associated with amnesic shellfish poisoning (ASP) including "gastrointestinal illness, headache, dizziness, confusion, disorientation, permanent short-term memory deficits, and motor weakness" (Ekstrom et al. 2020). There have been several harmful algal blooms (HABs) of *Pseudo-nitzschia* that have occurred off the United States West Coast since the 1990s, contaminating marine life, killing marine birds, and impacting the economy and culture of coastal communities (Ekstrom et al. 2020). One of the most recent HABs of *Pseudo-nitzschia* occurred in 2015 off the United States West Coast, spreading from southeastern Alaska to Santa Barbara, California (Ekstrom et al. 2020, Moore et al. 2020). It has been found that ocean acidification and warmer climate could have influenced the impact of the HAB; this highlights the important role that scientists and organizations such as the National Oceanic and Atmospheric Administration (NOAA) have in monitoring ocean conditions and phytoplankton biodiversity along the West Coast in order to observe levels of *Pseudo-nitzschia,* predict HAB occurrences, and mitigate their impact (Ekstrom et al. 2020, Moore et al. 2020). Currently, many policy-makers are working closely with scientists to improve upon HAB monitoring and develop risk management strategies (Buteyko 2010, Ekstrom et al. 2020, Moore et al. 2020).

Rhizosolenia setigera

Bacillariophyceae (Class)
- Biddulphiales (Order)
  - Rhizosoleniineae (Suborder)
    - Rhizosoleniaceae (Family)
      - *Rhizosolenia* (Genus)
        - *Rhizosolenia setigera* (Species)

(Tomas et al. 1997)

Rhizosolenia setigera is characterized by elongated cylindrical, rod-like cells that taper at the ends into long, generally straight spines (**Figure 14A**) (Cupp 1943). The valves are conical and 4-20 μm in diameter (Cupp 1943, Tomas et al. 1997). Under SEM, areolae appear poroid and a labiate process can be seen (Tomas et al. 1997). *R. setigera* is a neritic and north temperate species (**Figure 14B**) (Boyer 1927, Cupp 1943, Ocean Biodiversity Observation System 2021).

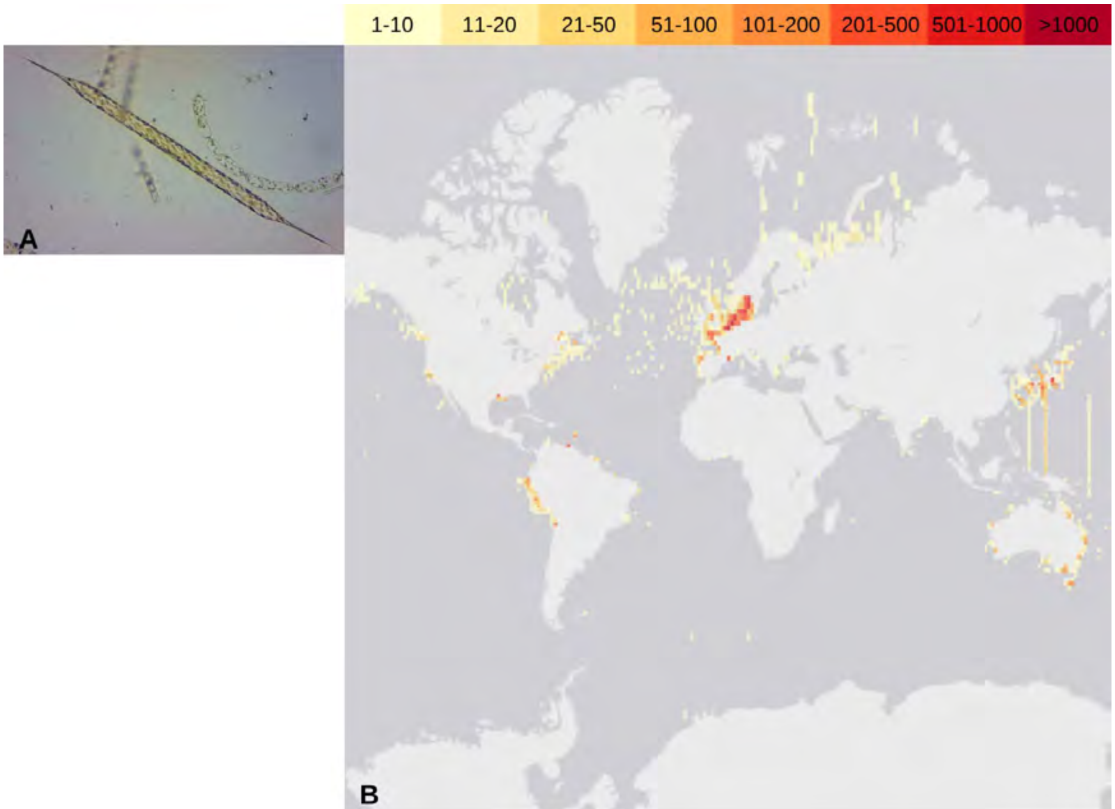


Figure 14. *Rhizosolenia setigera.* **(A)** LM image of *R. setigera* (LM image by Sarka Martinez). **(B)** global distribution of *R. setigera* based on Ocean Biodiversity Observation System (2021). Color scale indicates the number of records at the sampling site out of 25,303 global records.

Skeletonema costatum

Bacillariophyceae (Class)
Biddulphiales (Order)
Coscinodiscineae (Suborder)
Thalassiosiraceae (Family)
Skeletonema (Genus)
Skeletonema costatum (Species)
(Tomas et al. 1997)

Skeletonema costatum is a straight chain of slightly convex cells with a diameter of 2-21 μm and a height (pervalvar axis) of 2-61 μm; the cells form a chain by connecting to one another via tube-like processes at the valve margin (**Figure 15A**) (Boyer 1927, Tomas et al. 1997). The processes are approximately 8 μm and form a distinct line where they intersect with the processes of the adjacent cell (Boyer 1927). Additionally, these processes are permanently connected to one another, meaning that even with acid treatment to remove organic material, the cells remain attached to one another (Tomas et al. 1997). *S. costatum* is a neritic and cosmopolitan species that is spread out in all seas and is particularly abundant during the spring (**Figure 15B**) (Boyer 1927, Ocean Biodiversity Observation System 2021).

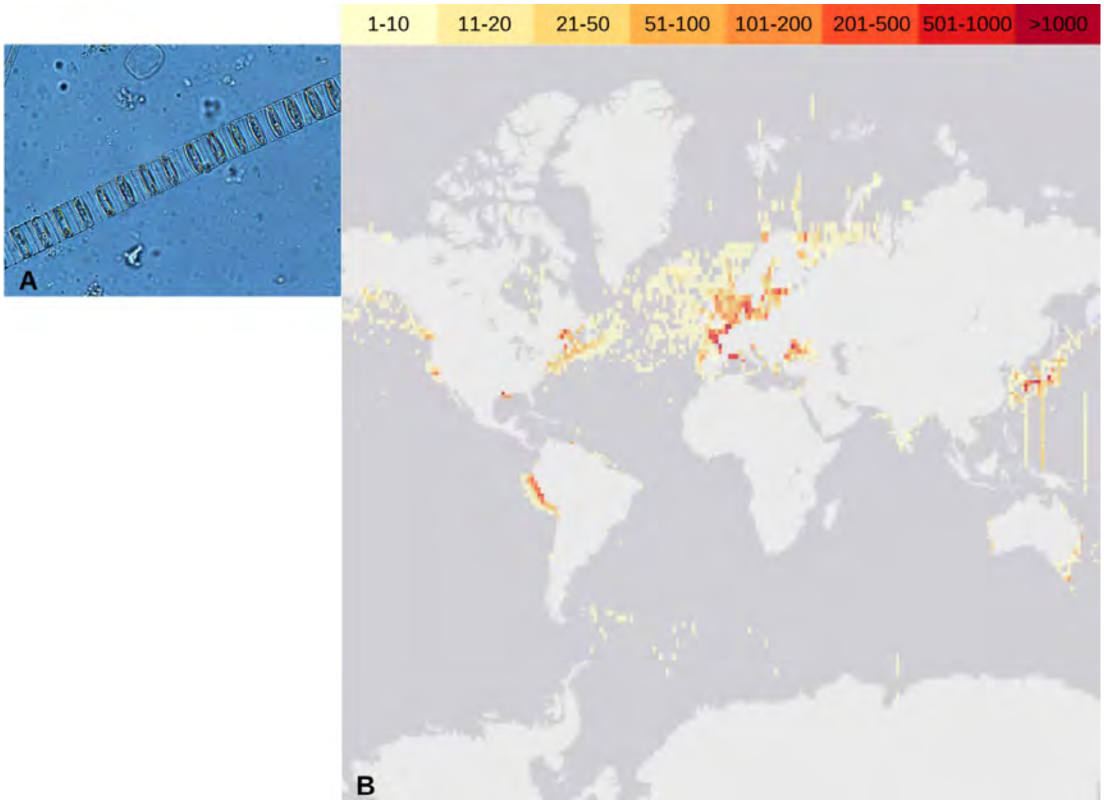


Figure 15. *Skeletonema costatum.* **(A)** LM image of *S. costatum.* **(B)** global distribution of *S. costatum* based on Ocean Biodiversity Observation System (2021). Color scale indicates the number of records at the sampling site out of 56,828 global records.

***Thalassiosira* Species**

Bacillariophyceae (Class)
Biddulphiales (Order)
Coscinodiscineae (Suborder)
Thalassiosiraceae (Family)
Thalassiosira (Genus)
Skeletonema costatum (Species)
(Tomas et al. 1997)

The genus *Thalassiosira* has over 100 species, and it has become one of the most well-studied marine phytoplankton due to the modern application of electron microscopy which provides greater detailed views of morphological characteristics for the identification of species (Garcia and Odebrecht 2009, Hassle 1973, Hoppenrath et al. 2007, Tomas et al. 1997). Several *Thalassiosira* species keys have been made, each of them starting with different morphological characteristics (Fryxell 1977, Tomas et al. 1997). *Thalassiosira* species are generally characterized by disk-shaped or drum-shaped cells with rounded or flat edges and are usually found united in flexible chains via gelatinous threads or associated in clusters via a gelatinous sheath (**Figure 16A**) (Cupp 1943, Tomas et al. 1997). Under LM, differences between species can be seen in regards to valve shape and the length and thickness of connecting threads (Tomas et al. 1997). Under SEM, ornamentation such as the number and type of processes (whether strutted or labiate) and the pattern of areolae can help distinguish species from one another (Hoppenrath et al. 2007, Li et al. 2013). *Thalassiosira* species are neritic, arctic, and temperate (**Figure 16B**) (Cupp 1943, Fryxell 1977, Ocean Biodiversity Observation System 2021).

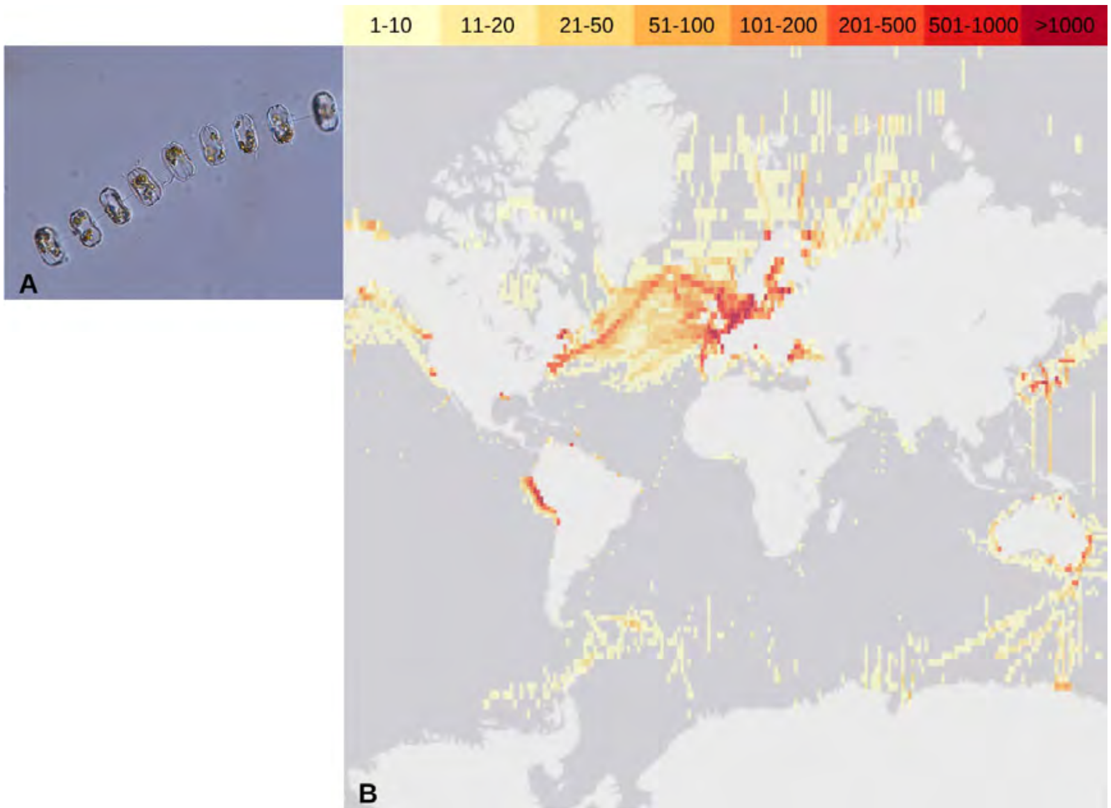


Figure 16. *Thalassiosira* species. **(A)** LM image of *Thalassiosira* species. **(B)** global distribution of *Thalassiosira* species based on Ocean Biodiversity Observation System (2021). Color scale indicates the number of records at the sampling site out of 201,302 records.

Trieres mobiliensis

Bacillariophyceae (Class)
Triceratiales (Order)
Triceratiaceae (Family)
Trieres (Genus)
Trieres mobiliensis (Species)
(Tomas et al. 1997)

Trieres mobiliensis is the currently accepted species name for the commonly referred to species *Biddulphia mobiliensis* (DiatomBase 2021). The cells are either solitary or found in short chains of elliptical to lanceolate, convex valves in valve view or rectangular valves in girdle view (**Figure 17A**) (Boyer 1927, Lavigne et al. 2015, Scott and Marchant 2005, Sims et al. 2018).

The shape of *T. mobiliensis* in valve view has also been described as dodecagonal (Lavigne et al. 2015). Cells can be 30-130 µm in height (pervalvar axis), 27-200 µm along the apical axis, and 22-43 µm along the transapical axis (Boyer 1927, Lavigne et al. 2015, Scott and Marchant 2005, Sims et al. 2018). Small conical elevations towards the center of the valves taper and extend into long spines (Boyer 1927, Sims et al. 2018). Two to four long and curved labiate processes can also be seen under LM extending diagonally from the valve margin (Cupp 1943, Scott and Marchant 2005). Under SEM, areolae appear hexagonal and loculate or chamber-like, there are small spines (spinules) on the valve face, and a central annulus, or ring without areolae, surrounds poroids (Lavign et al. 2015, Ross et al. 1979, Simonsen 1975, Sims et al. 2018, Tomas et al. 1997). *T. mobiliensis* is a neritic, temperate, and south temperate species (**Figure 17B**) (Boyer 1927, Cupp 1943).

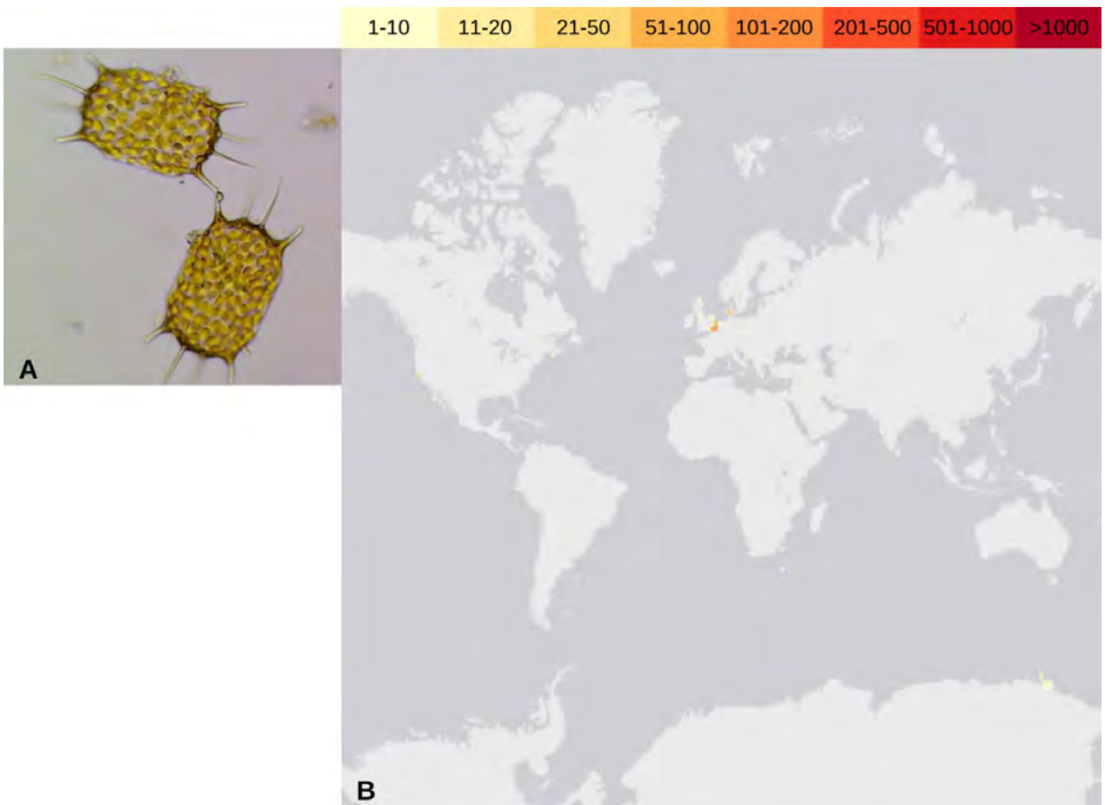


Figure 17. *Trieres mobiliensis.* **(A)** LM image of *T. mobiliensis* (LM image by GTMResearchReserve). **(B)** global distribution of *T. mobiliensis* based on Ocean Biodiversity Observation System (2021). Color scale indicates the number of records at the sampling site out of 582 records.

Challenges in the construction of dichotomous taxonomic keys

Taxonomy is always changing. This is evident through species synonymy (**Table 1, Appendix A**). Synonymy refers to the scientific names that have been given to a taxon, such as variations in spelling and emendations (Gardner and Hayssen 2004). Two types of synonyms include heterotypic (taxonomic) synonyms and homotypic (nomenclatural) synonyms (McNeill et al. 2012). Heterotypic synonyms are names based on different type specimens and are therefore determined by taxonomist opinions (McNeill et al. 2012). Homotypic synonyms are names based on the same type specimen and are determined by nomenclatural rules set by the International Code of Nomenclature for algae, fungi, and plants (ICN) (McNeill et al. 2012). Over time, species names change as advancements in technology, such as molecular techniques and electron microscopy, allow for the identification of unique molecular markers and specific morphology not previously distinguishable (Leliart 2021). While some changes in naming conventions are more straightforward, such as the renaming of the genus *Streptotheca* into *Heliotheca,* some other changes may lead to some confusion over where species fit in taxonomically. For example, *Bacillaria paxillifer* has three recognized synonyms: *Bacillaria paradoxa, Nitzschia paradoxa,* and *Vibrio paxillifer.* Of these three synonyms, two of them are from entirely different genera. Additionally, some genera are similar to one another in morphology, with only a slight difference separating the two; as a result, there have been disputes over which genus certain species belong to. This is why we tend to see an interchange of naming between some *Thalassiosira* and *Coscinodiscus* species (such as *Thalassiosira anguste-lineata* which is currently accepted as *Coscinodiscus angustelineatus*), between some *Guinardia* and *Eucampia* species (such as *Guinardia striata* which is currently accepted as *Eucampia striata*), and between some *Odontella, Biddulphia,* and *Trieres* species (such as *Odontella weissflogii, Biddulphia mobiliensis,* and the currently accepted *Trieres mobiliensis*).

Morphological variation also contributes to the difficulty in taxonomic identification (Battarbee 1986). Some species may not have enough distinguishable differences in characteristics, resulting in the misidentification of species (Fischer and Bunke 2001, Pappas and Stoermer 2001). Additionally, ranges in size amongst individuals of a particular diatom species due to cell reproduction and division further contributes to this confusion (Battarbee 1986). Changes in size may also result in shape distortions which could impact species identification based on morphology (Pappas 2006). Furthermore, cells at different points in the diatom life cycle may look different from one another, resulting in misidentifications of a species as several species rather than one (Pappas 2006).

Additionally, since the 1800s there have been many different classification systems for the taxonomy of diatoms, contributing to the confusion that many non-taxonomists may encounter when identifying diatom species (Spamer and Theriot 1997, Williams et al. 2011). The most current classification system - which was primarily referenced in the construction of the technical and basic keys in this project - organizes diatoms by order Biddulphiales (centric diatoms) or order Bacillariales (pennate diatoms), then suborders, families, genera, and species (Tomas et al. 1997, Williams et al. 2011). However, previous classification systems have referred to centric diatoms as Centricae and pennate diatoms as Pennatae (Boyer 1927, Cupp 1943). These older classification systems differ from the current classification system because they included subsections, subfamilies, tribes, and sub-tribes (Cupp 1943, Smith and West 1853). Furthermore, the current classification system uses the suffix *-ineae* for suborders whereas older classification systems used the suffix *-atae* (Boyer 1927, Tomas et al. 1997). These and many more different classification systems arose as scientists discovered characteristics and considered them for the basis of determining species from one another (Williams et al. 2011). It is important that current naming structures and taxonomic classification systems are referenced when doing scientific research to prevent misuse and errors in species identification which contributes to conflicting nomenclature data (Spamer and Theriot 1997). For this reason, DiatomBase (2021) was used as a standard in determining the current accepted taxon name and synonyms of diatom species. Referencing current taxonomic literature is also critical because taxonomy is the only way biodiversity and evolution of diatoms can be properly assessed and quantified.

Contribution to public outreach

Ultimately, these keys will assist in the study of phytoplankton and the furthering of scientific education in the San Francisco Bay Area. As mentioned previously, there are several groups of that are studying and looking at San Francisco Bay phytoplankton. In particular, this project is in collaboration with the Gulf of Farallones Visitor Center (NOAA 2017), and "A Basic Key to Common Phytoplankton in San Francisco Bay" will be implemented into the marine education programs for children in grades kindergarten through high school to guide their exploration of phytoplankton. Within USF, these keys will support courses in the Department of Biology such as General Biology, and the upper division Oceanography course in which students sample and examine phytoplankton in San Francisco Bay (University of San Francisco 2021). Additionally, these keys will serve as a resource for continuing phytoplankton research at the University of San Francisco.

RECOMMENDATIONS FOR CONTINUING WORK

Although the two keys developed in the project were intended to serve as a guide of common diatoms found in San Francisco Bay, taxonomy is always changing. Additionally, the classification system used to guide the construction of the technical key is an artificial identification system based on hypotheses, and while this system is the most modern one, adjustments to this system may be made as more characteristics are considered, species are discovered, and technological advancements are developed (Williams et al. 2011). Therefore, these keys should be updated accordingly in the future. Additionally, some species, such as those in the genus *Coscinodiscus,* were grouped together in the technical key due to practical issues of differentiating the species from one another. Future research should analyze the morphological differences between the species and expand upon the current key. It is also worth noting that the technical key does not specify whether a morphological characteristic can be observed under the LM or under SEM only. Future work should clarify this or specify up to what node on the taxonomic trees LM is limited to as many individuals may not have access to SEM.

ACKNOWLEDGEMENTS

I would like to acknowledge and thank everyone who made this study possible, including: Dr. Deneb Karentz for her guidance throughout the study, Dr. Mary Jane Niles and Dr. Sangman Kim for their support in developing the keys, Janai Southworth and Justin Holl for their guidance in developing the basic key and collaboration to implement the key at the Visitor Center at Gulf of the Farallones National Marine Sanctuary (NOAA), Jeff Oda for assistance and maintenance of the scanning electron microscope, Theresa Keith for her previous research and collection samples that inspired this research, and the donors to the University of San Francisco Biology Gift Fund whose generosity contributed to the research grant that funded part of this study.

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IMAGE CREDITS

Unless otherwise indicated, all LM images were taken by Dr. Deneb Karentz from the University of San Francisco.

Figure 10B: LM image of *Chaetoceros curvisetus* by Stephanie Anderson retrieved from https://web.uri.edu/gso/research/plankton/data/

Figure 13A: LM image of *Rhizosolenia setigera* by Sarka Martinez retrieved from https://www.inaturalist.org/guide_taxa/356511

Figure 16A: LM image of *Trieres mobiliensis* by GTMResearchReserve retrieved from https://www.inaturalist.org/guide_taxa/353280

APPENDICES

Appendix A:

List of diatom species in San Francisco Bay included in "A Technical Key to Common Planktonic Diatoms in San Francisco Bay" (**Appendix B**) and taxonomic resources associated with each species.

Species	Synonym	Resources
Achnanthes sp. Bory		Cupp 1943, pp. 191-192 Tomas et al. 1997
Actinoptychus senarius Ehrenberg	*Actinoptychus undulatus* (Bailey) Ralfs	Boyer 1927, pp. 64-65 Scott and Marchant 2005, p. 51 Tomas et al. 1997, p. 141 (Plate 22)
Actinoptychus sp. Ehrenberg		Cupp 1943, pp. 66-67 Tomas et al. 1997
Amphiprora sp. Ehrenberg		Cupp 1943, p. 197 Smith and West 1853, p. 43 Tomas et al. 1997
Arachnoidiscus ornatus Ehrenberg		Boyer 1927, p. 69 Tanimura et al. 2005
Asterionella formosa Hassall		Boyer 1927, p. 213 Pappas and Stoermer 2001
Asterionella japonica Cleve	*Asterionellopsis glacialis* (Castracane) Round	Cupp 1943, pp. 188-189 Tomas et al. 1997, p. 241 (Plate 50)
Asterolampra sp. Ehrenberg		Cupp 1943, p. 68 Tomas et al. 1997
Asteromphalus Ehrenberg		Cupp 1943, p. 68 Tomas et al. 1997
Asteromphalus hookeri Ehrenberg	*Asteromphalus humboldtii* Ehrenberg	Boyer 1927, pp. 74-75 Scott and Marchant 2005, p. 14 Tomas et al. 1997 (Plate 25, Table 31)
Bacillaria paxillifer (Müller) Marsson	*Bacillaria paradoxa* Gmelin *Nitzschia paradoxa* (Gmelin) Grunow *Vibrio paxillifer* Müller	Cupp 1943, pp. 206-207 Tomas et al. 1997, p. 293 (Plate 66)
Biddulphia sp. Gray		Cupp 1943, pp. 151-152 Tomas et al. 1997
Chaetoceros affinis Lauder	*Chaetoceros affine* Lauder *Chaetoceros schuttii* Cleve	Cupp 1943, pp. 124-126 Tomas et al. 1997, p. 216 (Plate 46, Table 54)
Chaetoceros constrictus Gran		Cupp 1943, pp. 122-123 Tomas et al. 1997, p. 209 (Plate 43, Table 50)
Chaetoceros curvisetus Cleve		Cupp 1943, pp. 137-138 Scott and Marchant 2005, p. 31 Tomas et al. 1997, p. 211 (Plate 44, Table 51)
Chaetoceros debilis Cleve	*Chaetoceros debile* Cleve	Cupp 1943, pp. 138-140 Scott and Marchant 2005, pp. 31-32 Tomas et al. 1997, p. 211 (Plate 44, Table 51)
Chaetoceros decipiens Cleve		Boyer 1927, pp. 108-109 Cupp 1943, pp. 115-116 Tomas et al. 1997, p. 204 (Plate 42, Table 49)
Chaetoceros didymus Ehrenberg	*Chaetoceros didymum* Ehrenberg	Boyer 1927, pp. 107-108 Cupp 1943, pp. 120-122 Tomas et al. 1997, p. 192 (Plate 43, Table 50)
Chaetoceros radicans Schütt		Cupp 1943, pp. 141-142 Tomas et al. 1997, p. 213 (Plate 45, Table 52)

List of diatom species in San Francisco Bay included in “A Technical Key to Common Planktonic Diatoms in San Francisco Bay” (**Appendix B**) and taxonomic resources associated with each species.

Species	Synonym	Resources
Chaetoceros socialis Lauder		Cupp 1943, p. 143 Scott and Marchant 2005, p. 37 Tomas et al. 1997, p. 221 (Plate 47)
Chaetoceros spp. Ehrenberg		Cupp 1943, pp. 100-103 Tomas et al. 1997, pp. 189-193 (Plates 38-47, Tables 51-56)
Chaetoceros tortissimus Gran		Cupp 1943, p. 142 Scott and Marchant 2005, pp. 37-38 Tomas et al. 1997, p. 215 (Plate 45, Table 52)
Corethron hystrix Hensen	*Corethron criophilum var. histrix* (Hensen) Hendey	Boyer 1927, pp. 114-115 Cupp 1943, p. 70-74
Corethron pennatum (Grunow) Ostenfeld		Scott and Marchant 2005, p. 65
Corethron sp. Castracane		Cupp 1943, p. 70 Tomas et al. 1997
Coscinodiscus angustelineatus Schmidt	*Thalassiosira anguste-lineata* (Schmidt) Fryxell and Hasle	Hoppenrath et al. 2007 Tomas et al. 1997, p. 71 (Plate 9, Table 11)
Coscinodiscus curvatulus var. curvatulus Grunow	*Actinocyclus curvatulus* (Grunow) Cleve	Boyer 1927, p. 48 Cupp 1943, pp. 54-55 Scott and Marchant 2005, p. 52-54 Tomas et al. 1997, p. 121 (Plate 19, Table 25)
Coscinodiscus lentiginosus var. lentiginosus Janisch	*Thalassiosira lentiginosa* (Janisch) Fryxell	Boyer 1927, p. 49 Fryxell 1977 Scott and Marchant 2005, pp.100, 103 Tomas et al. 1997, p. 79 (Plate 10, Table 13)
Coscinodiscus oculus-iridis Ehrenberg		Boyer 1927, p. 57 Cupp 1943, pp. 62-63 Scott and Marchant 2005, p. 44
Coscinodiscus spp. Ehrenberg		Cupp 1943, pp. 50-52 Tomas et al. 1997
Detonula sp. Schütt ex De Toni		Tomas et al. 1997
Ditylum brightwellii (West) Grunow	*Triceratium brightwellii* West	Cupp 1943, 148-150 Tomas et al. 1997, pp. 230-231 (Plate 48, Table 58)
Ditylum sp. Bailey ex Bailey		Cupp 1943, p. 148 Tomas et al. 1997
Eucampia sp. Ehrenberg		Cupp 1943, p. 145 Tomas et al. 1997
Eucampia striata Stolterfoth	*Guinardia striata (Stolterfoth)* Hasle *Rhizosolenia stolterfothii* Peragallo	Cupp 1943, pp. 83-84 Tomas et al. 1997, p. 163 (Plate 31, Table 36)
Eucampia zodiacus Ehrenberg		Cupp 1943, p. 145-146 Tomas et al. 1997, p. 175 (Plate 34, Table 40) Boyer 1927, p. 116
Gyrosigma balticum (Ehrenberg) Rabenhorst	*Pleurosigma balticum* (Ehrenberg) Smith	Smith and West 1853, p. 66
Heliotheca sp. Ricard	*Streptotheca* sp. Shrubsole	Cupp 1943, p. 147
Heliotheca tamesis (Shrubsole) Ricard	*Streptotheca thamensis* Shrubsole	Cupp 1943, p. 147-148 Hernández-Becerril et al. 2013 Tomas et al. 1997, pp. 234-235 (Plate 48)
Hobaniella longicruris (Greville) Sims and Williams	*Odontella longicruris* (Greville) Hoban *Biddulphia longicruris var. longicruris* Greville	Ashworth et al. 2013 Cupp 1943, pp. 154-156 Lavigne et al. 2015 Sims et al. 2018 Tomas et al. 1997, pp. 238-239 (Plate 49, Table 62)

List of diatom species in San Francisco Bay included in “A Technical Key to Common Planktonic Diatoms in San Francisco Bay” (**Appendix B**) and taxonomic resources associated with each species.

Species	Synonym	Resources
Isthmia nervosa Kützing		Boyer 1927, p. 140 Cupp 1943, pp. 166-167
Lauderia confervacea Cleve	*Detonula confervacea* (Cleve) Gran	Boyer 1927, p. 102 Tomas et al. 1997, pp. 35-36 (Plate 1, Table 2)
Lauderia sp. Cleve		Cupp 1943, p. 74 Tomas et al. 1997
Leptocylindrus danicus Cleve		Cupp 1943, p. 77-78 Scott and Marchant 2005, p. 65 Tomas et al. 1997, p. 93 (Plate 14, Table 18)
Lithodesmium undulatum Ehrenberg		Cupp 1943, p. 150-151 Tomas et al. 1997, pp. 232-234 (Plate 48, Table 60)
Melosira arctica var. arctica Dickie	*Melosira arctica* (Ehrenberg) Ralfs *Gaillonella arctica* (Dickie) Ehrenberg	Kaczmarska and Jahn 2006 Tomas et al. 1997, p. 89 (Plate 14, Table 16)
Melosira moniliformis (Müller) Agardh		Cupp 1943, pp. 39-40
Melosira sp. Agardh		Cupp 1943, p. 39 Lipsey 1987 Tomas et al. 1997
Melosira varians Agardh		Lipsey 1987, p. 266
Navicula challengeri Grunow	*Tropidoneis antarctica* (Grunow) Cleve *Membraneis challengeri* (Grunow) Paddock *Amphiprora challengeri* (Grunow) De Toni	Scott and Marchant 2005, p. 154 Tomas et al. 1997, p. 287 (Plate 64, Table 72)
Navicula sp. Bory de Saint-Vincent		Cupp 1943, pp. 192-193 Tomas et al. 1997
Nitzschia closterium (Ehrenberg) Smith	*Cylindrotheca closterium* (Ehrenberg) Lewin and Reimann *Phaeodactylum tricornutum* Bohlin	Cupp 1943, p. 200 Smith and West 1853, pp. 42-43 Tomas et al. 1997, p. 269 (Plate 60), p. 294 (Plate 66)
Nitzschia longissima (Brébisson) Ralfs	*Nitzschiella longissima* (Brébisson) Rabenhorst	Cupp 1943, pp. 200-201 Scott and Marchant 2005, p. 191 Tomas et al. 1997, p. 329 (Plate 74)
Nitzschia sigma (Kützing) Smith	*Sigmatella sigma* (Kützing) Frenguelli	Smith and West 1853, p. 39
Nitzschia sp. Hassall		Cupp 1943, p. 199 Smith and West 1853, pp. 38-43 Tomas et al. 1997
Odontella aurita (Lyngbye) Agardh	*Biddulphia aurita* (Lyngbye) Brébisson	Ashworth et al. 2013 Cupp 1943, pp. 160-162 Scott and Marchant 2005, p. 48 Sims et al. 2018 Tomas et al. 1997, pp. 236-239 (Plate 49, Table 62)
Odontella obtusa Kützing	*Biddulphia aurita var. obtusa* (Kützing) Hustedt	Boyer 1927, p. 123 Cupp 1943, pp. 162-163 Lavigne et al. 2015
Paralia sulcata (Ehrenberg) Cleve	*Melosira sulcata* (Ehrenberg) Kützing *Gaillionella sulcata* Ehrenberg *Orthoseira marina* Smith	Cupp 1943, pp. 39-40 Yun et al. 2016 Tomas et al. 1997, p. 91 (Plate 14)
Pleurosgima spp. Smith		Cupp 1943, p. 194 Tomas et al. 1997
Porosira sp. Jorgensen		Tomas et al. 1997
Pseudo-nitzschia sp. Peragallo		Tomas et al. 1997, p. 307

List of diatom species in San Francisco Bay included in “A Technical Key to Common Planktonic Diatoms in San Francisco Bay” (**Appendix B**) and taxonomic resources associated with each species.

Species	Synonym	Resources
Rhizosolenia calcar-avis Schultze	*Pseudosolenia calcar-avis* (Schultze) Sundström	Cupp 1943, pp. 89-90 Tomas et al. 1997, p. 160 (Plate 30)
Rhizosolenia robusta Norman ex Ralfs		Cupp 1943, pp. 83-85 Tomas et al. 1997, p. 159 (Plate 30)
Rhizosolenia semispina Hensen	*Rhizosolenia hebetata* (Hensen) Margalef *Rhizosolenia hebetata f. semispina (Hensen) Gran*	Armand and Zielinski 2001 Boyer 1927, pp. 100-101 Cupp 1943, pp. 88-89 Scott and Marchant 2005, p. 81 Tomas et al. 1997, pp. 149-150 (Plate 27, Table 33)
Rhizosolenia setigera Brightwell		Boyer 1927, p. 100 Cupp 1943, p. 88 Tomas et al. 1997, p. 157 (Plate 30)
Rhizosolenia sp. Brightwell	*Proboscia* sp. Sundstrom	Armand and Zielinski 2001 Cupp 1943, pp. 79-80 Lipsey 1987 Tomas et al. 1997
Rhizosolenia styliformis Brightwell		Armand and Zielinski 2001 Cupp 1943, p. 87 Scott and Marchant 2005, p. 83-84 Tomas et al. 1997, pp. 144-146 (Plate 26, Table 32)
Skeletonema costatum (Greville) Cleve		Boyer 1927, p. 63 Cupp 1943, pp. 43-44 Tomas et al. 1997, pp. 44-45 (Plate 3, Table 6)
Skeletonema sp. Greville		Cupp 1943, p. 43 Tomas et al. 1997
Stephanopyxis sp. Ehrenberg		Cupp 1943, p. 40 Tomas et al. 1997
Stephanopyxis turris (Greville) Ralfs		Boyer 1927, p. 35 Cupp 1943, pp. 40-41
Synedra nitzschioides f. nitzschioides Grunow	*Thalassionema nitzschioides* (Grunow) Mereschkowsky *Thalassiothrix nitzschioides* Grunow	Boyer 1927, pp. 207-208 Cupp 1943, pp. 182-183 Scott and Marchant 2005, pp. 144-145 Tomas et al. 1997, pp. 257-262 (Plate 57, Table 66)
Thalassiosira nordenskioeldii Cleve		Boyer 1927, p. 62 Cupp 1943, pp. 46-67 Hoppenrath et al. 2007 Li et al. 2013 Tomas et al. 1997, p. 56 (Plate 5, Table 7)
Thalassiosira rotula Meunier	*Coscinodiscus rotulus* (Meunier) Cleve-Euler	Cupp 1943, pp. 49-50 Hoppenrath et al. 2007 Tomas et al. 1997, p. 70 (Plate 8, Table 10)
Thalassiosira spp. Cleve		Cupp pp. 45-46 Fryxell 1977 Garcia and Odebrecht 2009 Hoppenrath et al. 2007 Li et al. 2013 Tomas et al. 1997
Thalassiosira subtilis (Ostenfeld) Gran		Cupp 1943, pp. 49, 51 Hoppenrath et al. 2007
Thalassiothrix mediterranea var. pacifica Cupp	*Lioloma pacificum* (Cupp) Hasle	Cupp 1943, pp. 185-186 Tomas et al. 1997, pp. 254-257 (Plate 53, Plate 54, Table 65)
Thalassiothrix sp. Cleve and Grunow		Cupp 1943, p. 183 Tomas et al. 1997

List of diatom species in San Francisco Bay included in “A Technical Key to Common Planktonic Diatoms in San Francisco Bay” (**Appendix B**) and taxonomic resources associated with each species.

Species	Synonym	Resources
Triceratium alternans Bailey	*Trigonium alternans* (Bailey) Mann *Biddulphia alternans* (Bailey) Van Heurck	Ashworth et al. 2013 Boyer 1927, pp. 134-135 Cupp 1943, pp. 165-166
Triceratium sp. Ehrenberg		Tomas et al. 1997
Trieres mobiliensis (Bailey) Ashworth and Theriot	*Biddulphia mobiliensis* (Bailey) Grunow *Odontella weissflogii* Grunow	Ashworth et al. 2013 Boyer 1927, p. 122 Cupp 1943, p. 153 Lavigne et al. 2015 Sims et al. 2018 Scott and Marchant 2005, pp. 48-51
Tropidoneis sp. Cleve		Cupp 1943, p. 197 Tomas et al. 1997

Appendix B:

"A Technical Key to Common Planktonic Diatoms in San Francisco Bay" is a digitally interactive document that contains (1) a list of common diatoms found in San Francisco Bay, (2) detailed dichotomous taxonomic decision trees with morphological descriptions, (3) a phytoplankton terminology list, and (4) a diatom photo gallery. This technical key is intended for use by an audience familiar with phytoplankton research. Highlighted words indicate that they are terminology which can be looked up in the back of the guide.

A Technical Key to Common Planktonic Diatoms in San Francisco Bay

SF PHYTOPLANKTON KEYS

UNIVERSITY OF SAN FRANCISCO, DEPARTMENT OF BIOLOGY

Table of Contents

NOTE:
Click on the species name to be taken to its place on the taxonomic trees.

Species	**Synonym**
Achnanthes sp. Bory	
Actinoptychus senarius Ehrenberg	*Actinoptychus undulatus* (Bailey) Ralfs
Actinoptychus sp. Ehrenberg	
Amphiprora sp. Ehrenberg	
Arachnoidiscus ornatus Ehrenberg	
Asterionella formosa Hassall	
Asterionella japonica Cleve	*Asterionellopsis glacialis* (Castracane) Round
Asterolampra sp. Ehrenberg	
Asteromphalus Ehrenberg	
Asteromphalus hookeri Ehrenberg	*Asteromphalus humboldtii* Ehrenberg
Bacillaria paxillifer (Müller) Marsson	*Bacillaria paradoxa* Gmelin *Nitzschia paradoxa* (Gmelin) Grunow *Vibrio paxillifer* Müller
Biddulphia sp. Gray	
Chaetoceros affinis Lauder	*Chaetoceros affine* Lauder *Chaetoceros schuttii* Cleve
Chaetoceros constrictus Gran	
Chaetoceros curvisetus Cleve	
Chaetoceros debilis Cleve	*Chaetoceros debile* Cleve
Chaetoceros decipiens Cleve	
Chaetoceros didymus Ehrenberg	*Chaetoceros didymum* Ehrenberg
Chaetoceros radicans Schütt	
Chaetoceros socialis Lauder	
Chaetoceros spp. Ehrenberg	
Chaetoceros tortissimus Gran	
Corethron hystrix Hensen	*Corethron criophilum var. histrix* (Hensen) Hendey
Corethron pennatum (Grunow) Ostenfeld	
Corethron sp. Castracane	

Species	**Synonym**
Coscinodiscus angustelineatus Schmidt	*Thalassiosira anguste-lineata* (Schmidt) Fryxell & Hasle
Coscinodiscus curvatulus var. curvatulus Grunow	*Actinocyclus curvatulus* (Grunow) Cleve
Coscinodiscus lentiginosus var. lentiginosus Janisch	*Thalassiosira lentiginosa* (Janisch) Fryxell
Coscinodiscus oculus-iridis Ehrenberg	
Coscinodiscus spp. Ehrenberg	
Detonula sp. Schütt ex De Toni	
Ditylum brightwellii (West) Grunow	*Triceratium brightwellii* West
Ditylum sp. Bailey ex Bailey	
Eucampia sp. Ehrenberg	
Eucampia striata Stolterfoth	*Guinardia striata* (Stolterfoth) Hasle *Rhizosolenia stolterfothii* Peragallo
Eucampia zodiacus Ehrenberg	
Gyrosigma balticum (Ehrenberg)Rabenhorst	*Pleurosigma balticum* (Ehrenberg) Smith
Heliotheca Ricard	*Streptotheca* sp. Shrubsole
Heliotheca tamesis (Shrubsole) Ricard	*Streptotheca thamensis* Shrubsole
Hobaniella longicruris (Greville) Sims & Williams	*Odontella longicruris* (Greville) Hoban *Biddulphia longicruris var. longicruris* Greville
Isthmia nervosa Kützing	
Lauderia confervacea Cleve	*Detonula confervacea* (Cleve) Gran
Lauderia sp. Cleve	
Leptocylindrus danicus Cleve	
Lithodesmium undulatum Ehrenberg	
Melosira arctica var. arctica Dickie	*Melosira arctica* (Ehrenberg) Ralfs *Gaillonella arctica* (Dickie) Ehrenberg
Melosira moniliformis (Müller) Agardh	
Melosira sp. Agardh	
Melosira varians Agardh	

Species	**Synonym**
Navicula challengeri Grunow	*Tropidoneis antarctica* (Grunow) Cleve *Membraneis challengeri* (Grunow) Paddock *Amphiprora challengeri* (Grunow) De Toni
Navicula sp. Bory de Saint-Vincent	
Nitzschia closterium (Ehrenberg) Smith	*Cylindrotheca closterium* (Ehrenberg) Lewin & Reimann *Phaeodactylum tricornutum* Bohlin
Nitzschia longissima (Brébisson) Ralfs	*Nitzschiella longissima* (Brébisson) Rabenhorst
Nitzschia sigma (Kützing) Smith	*Sigmatella sigma* (Kützing) Frenguelli
Nitzschia sp. Hassall	
Odontella aurita (Lyngbye) Agardh	*Biddulphia aurita* (Lyngbye) Brébisson
Odontella obtusa Kützing	*Biddulphia aurita var. obtusa* (Kützing) Hustedt
Paralia sulcata (Ehrenberg) Cleve	*Melosira sulcata* (Ehrenberg) Kützing *Gaillionella sulcata* Ehrenberg *Orthoseira marina* Smith
Pleurosigma spp. Smith	
Porosira sp. Jorgensen	
Pseudo-nitzschia sp. Peragallo	
Rhizosolenia calcar-avis Schultze	*Pseudosolenia calcar-avis* (Schultze) Sundström
Rhizosolenia robusta Norman ex Ralfs	
Rhizosolenia semispina Hensen	*Rhizosolenia hebetata* (Hensen) Margalef *Rhizosolenia hebetata f. semispina* (Hensen) Gran
Rhizosolenia setigera Brightwell	
Rhizosolenia sp. Brightwell	*Proboscia* sp. Sundstrom
Rhizosolenia styliformis Brightwell	
Skeletonema costatum (Greville) Cleve	
Skeletonema sp. Greville	

Species	**Synonym**
Stephanopyxis sp. Ehrenberg	
Stephanopyxis turris (Greville) Ralfs	
Synedra nitzschioides f. nitzschioides Grunow	*Thalassionema nitzschioides* (Grunow) Mereschkowsky *Thalassiothrix nitzschioides* Grunow
Thalassiosira nordenskioeldii Cleve	
Thalassiosira rotula Meunier	*Coscinodiscus rotulus* (Meunier) Cleve-Euler
Thalassiosira spp. Cleve	
Thalassiosira subtilis (Ostenfeld) Gran	
Thalassiothrix mediterranea var. pacifica Cupp	*Lioloma pacificum* (Cupp) Hasle
Thalassiothrix sp. Cleve & Grunow	
Triceratium alternans Bailey	*Trigonium alternans* (Bailey) Mann *Biddulphia alternans* (Bailey) Van Heurck
Triceratium sp. Ehrenberg	
Trieres mobiliensis (Bailey) Ashworth & Theriot	*Biddulphia mobiliensis (Bailey)* Grunow *Odontella weissflogii* Grunow
Tropidoneis sp. Cleve	

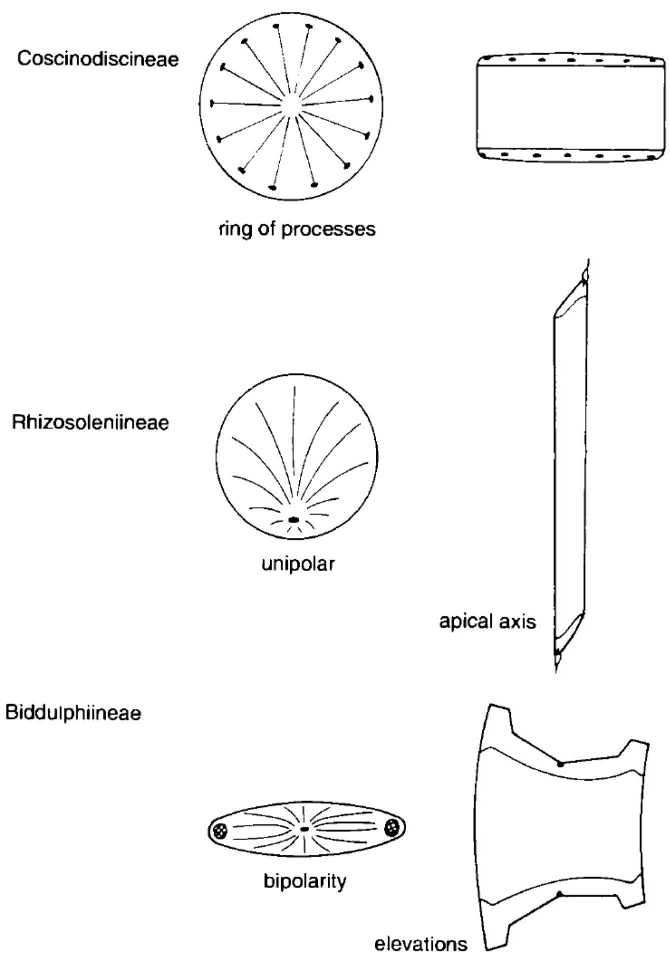
NOTE:
Click on "go to p.__" to be directly taken that page.

> START HERE <

Cells are radially symmetrical; valve striae arranged around a point, an annulus, or a central areola?

Yes

Order Biddulphiales (Centric Diatoms) → go to p.7



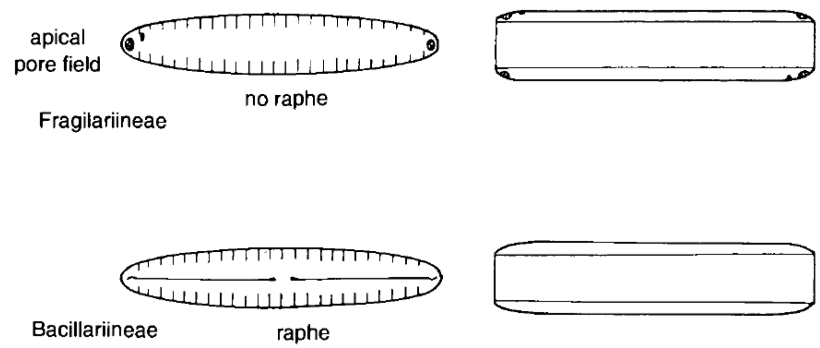
(Figure from Tomas et al. 1997)

No

Cells are bilaterally symmetrical; valve striae arranged basically in relation to a line?

Yes

Order Bacillariales (Pennate Diatoms) → go to p.8



(Figure from Tomas et al. 1997)

Order Biddulphiales - Valve striae arranged around a point, an annulus, or a central areola

Suborder Coscinodiscineae - Valves symmetrical and may have a marginal ring of processes

Family Thalassiosiraceae - cells in mucilage or in chains linked by threads from processes; one or a few labiate processes → go to p.10

Family Melosiraceae - strongly developed pervalvar axes; cells with a marginal ring of labiate processes and linked in chains → go to p.12

Family Leptocylindraceae - tight chains of cylindrical cells; valve center slightly convex or concave; short flap-like spines on valve margin → go to p.14

Family Coscinodiscaceae - cells solitary; marginal labiate processes with no external tubes → go to p.15

Family Stellarimaceae

Family Hemidiscaceae - cells cylindrical to discoid with radial areolae that differs between the face and mantle; one marginal ring of large labiate processes → go to p.16

Family Asterolampraceae - areolae on most of valve surface with hyaline central area and rays which terminate just before valve margin with a labiate process → go to p.17

Family Heliopeltaceae - valves divided into distinct sectors or radially waved → go to p.18

Suborder Rhizosoleniineae - Valves primarily unipolar; no marginal ring of processes

Family Rhizosoleniaceae - cylindrical cells in chains; single labiate process → go to p.19

Suborder Biddulphiineae - Valves primarily bipolar; no marginal ring of processes

Family Hemiaulaceae - close-chains with apertures between cells due to elevations; single labiate process; poroid areolae → go to p.21

Family Cymatosiraceae - cells either solitary, in tight chains by linking spines, or in loose ribbons; elevations low; only one process; heterovalvar → go to p.22

Family Chaetocerotaceae - cells solitary or in chains due to fused setae; long setae on valves → go to p.23

Family Lithodesmiaceae - cells solitary or in ribbons; valves with two to five angles; one bilabiate process per valve → go to p.26

Family Eupodiscaceae - cells have ocelli or pseudocelli and labiate processes with long external tubes → go to p.27

Order Bacillariales - Valve striae arranged basically in relation to a line

Suborder Fragilariineae - Araphid pennate diatoms; sternum present but indistinct in one family

Family Fragilariaceae - labiate process near one or both apices; apical pore at each apex; single rows of poroid areolae

Family Rhaphoneidaceae

Family Toxariaceae

go to p.28

Family Thalassionemataceae - cells solitary or in colonies; valves similar in shape to Toxariaceae but often twisted or curved; sternum wide; one labiate process at each end

go to p.29

Suborder Bacillariineae - Raphid pennate diatoms; sternum present

Family Achnanthaceae - heterovalvar (one valve with raphe and one without or with short slits)

go to p.30

Family Phaeodactylaceae

Family Naviculaceae - valve outlines linear, lanceolate, or elliptical; straight or sigmoid raphe

go to p.31

Family Bacillariaceae - cells usually in chains; valves long; raphe along one valve margin with bridges of silica beneath

go to p.32

Order Triceratiales

Family Triceratiaceae

Triangular frustules visible in valve view?

Yes

Genus *Triceratium*

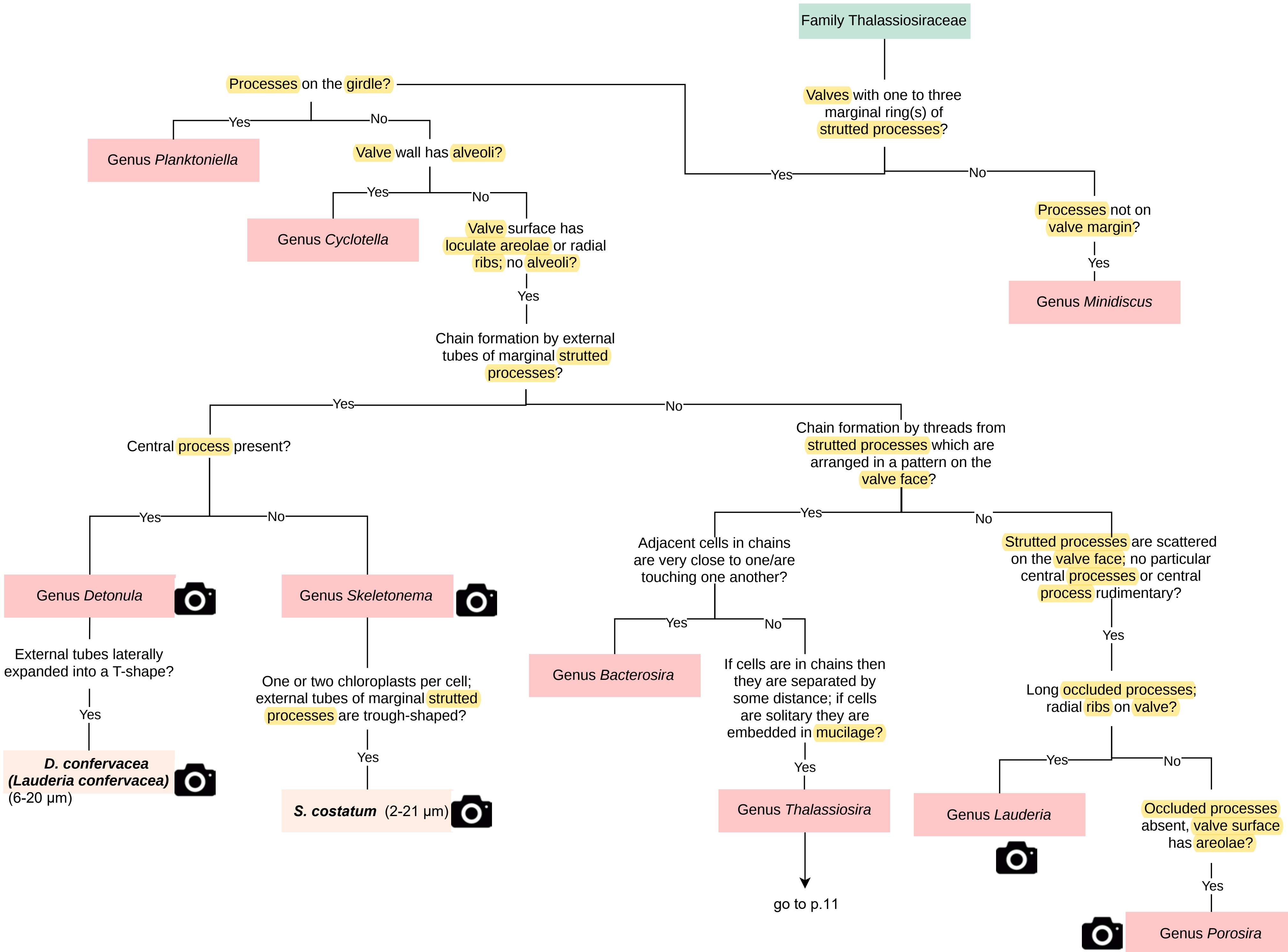
Sides of cells are straight or somewhat unevenly concave; mostly triangular cells but occasionally quadrangular; small areolae on corners, larger areolae in valve center and mantle; girdle band with pervalvar rows of areolae?

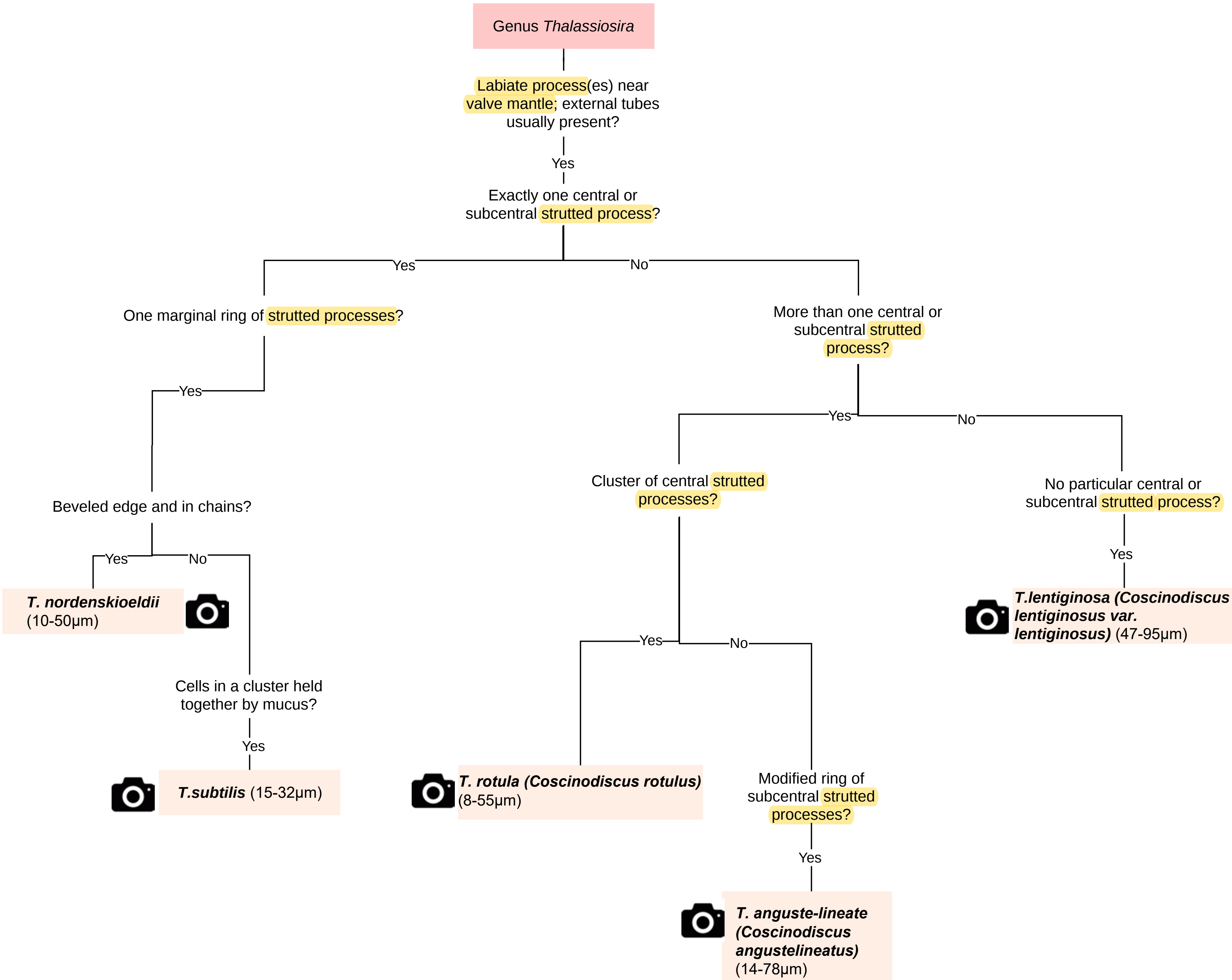
Yes

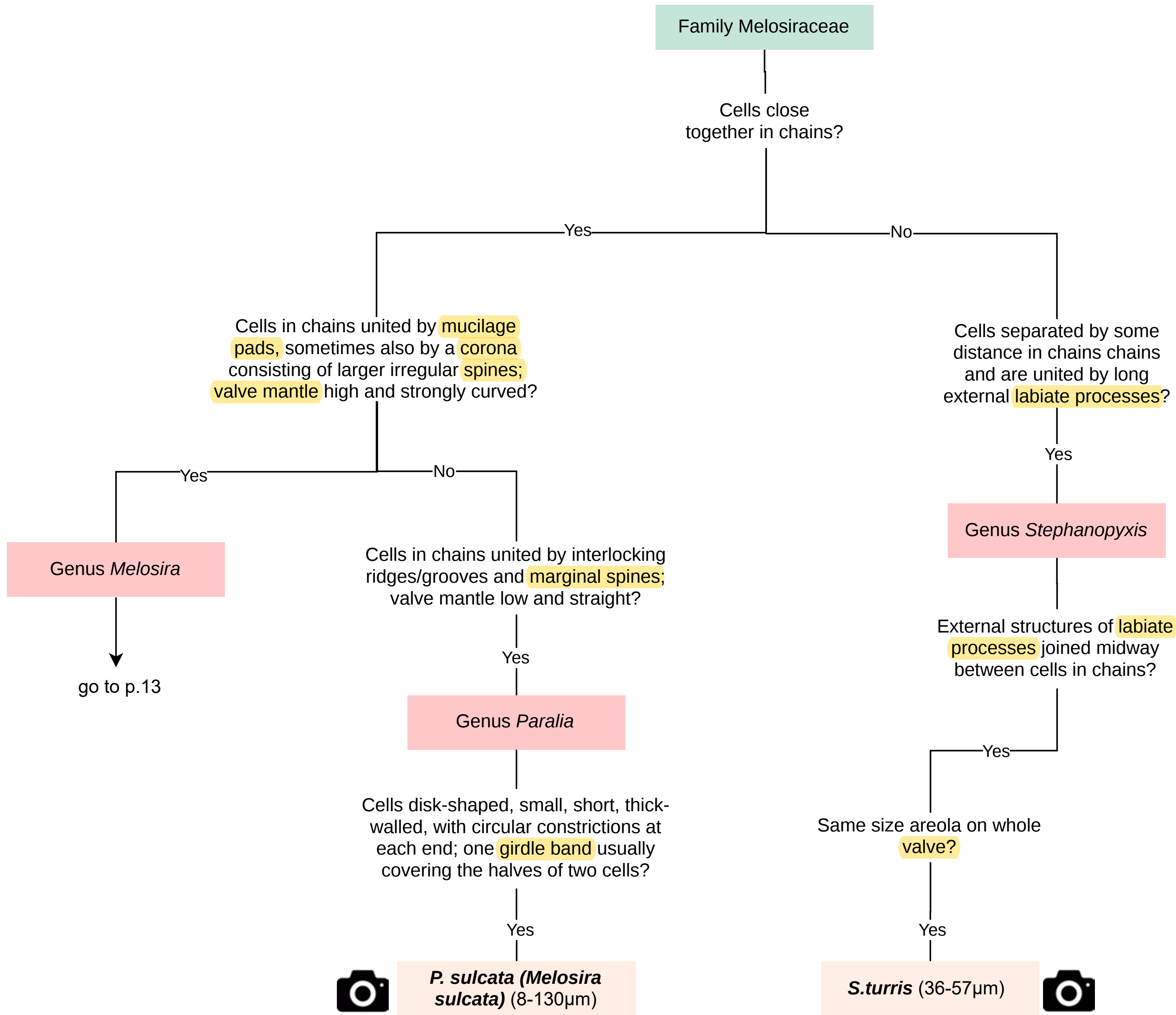
T. alternans (Trigonium alternans or ***Biddulphia alternans)*** (Length of side of valve 27–34µm; pervalvar axis 32-39µm)

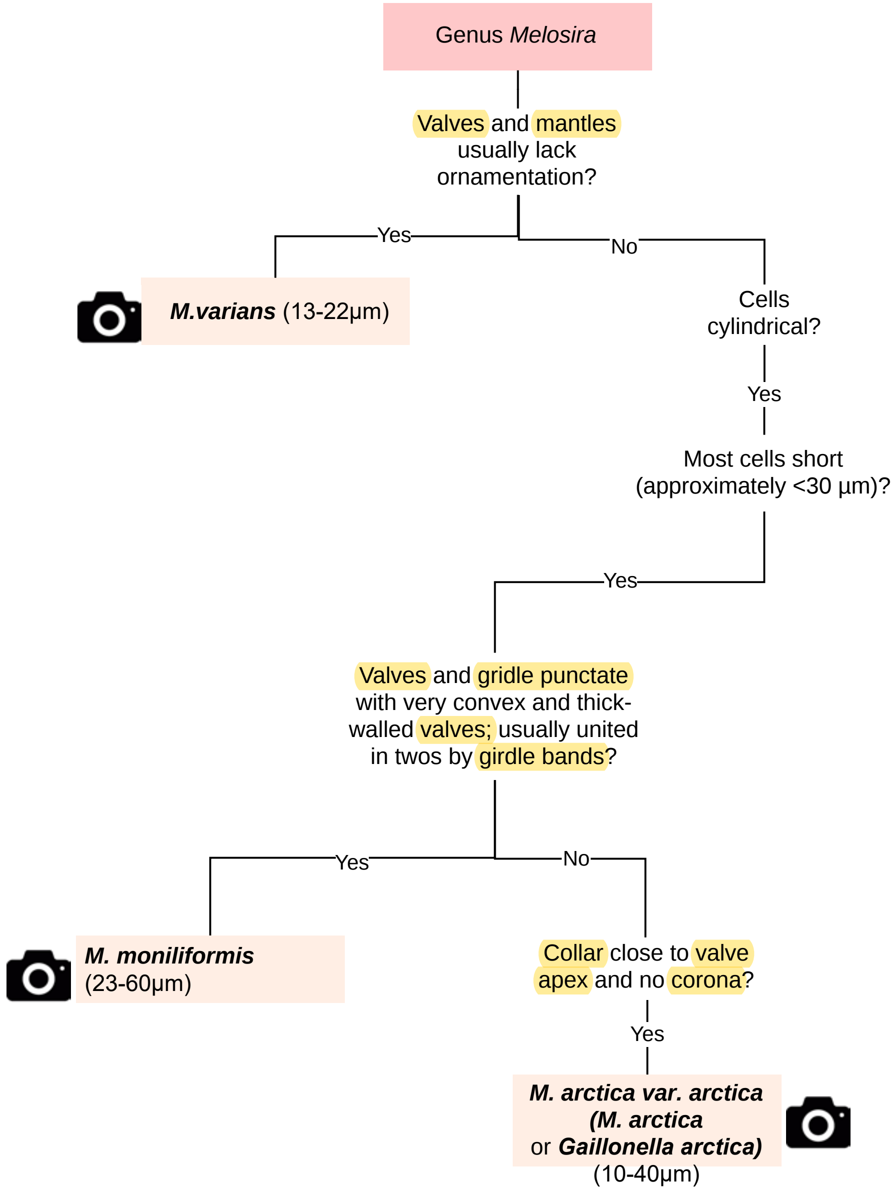
NOTE:
Click on the camera icon to see picture(s) of the genus or species.

NOTE:
Size ranges for terminal species are in reference to diameter unless otherwise specified.


Family Thalassiosiraceae
Valves with one to three marginal ring(s) of strutted processes?
Yes
No
Processes on the girdle?
Yes
No
Genus *Planktoniella*
Valve wall has alveoli?
Yes
No
Genus *Cyclotella*
Valve surface has loculate areolae or radial ribs; no alveoli?
Yes
Chain formation by external tubes of marginal strutted processes?
Yes
No
Central process present?
Yes
No
Genus *Detonula*
External tubes laterally expanded into a T-shape?
Yes
D. confervacea (Lauderia confervacea) (6-20 µm)
Genus *Skeletonema*
One or two chloroplasts per cell; external tubes of marginal strutted processes are trough-shaped?
Yes
S. costatum (2-21 µm)
Chain formation by threads from strutted processes which are arranged in a pattern on the valve face?
Yes
No
Adjacent cells in chains are very close to one/are touching one another?
Yes
No
Genus *Bacterosira*
If cells are in chains then they are separated by some distance; if cells are solitary they are embedded in mucilage?
Yes
Genus *Thalassiosira*
go to p.11
Strutted processes are scattered on the valve face; no particular central processes or central process rudimentary?
Yes
Long occluded processes; radial ribs on valve?
Yes
No
Genus *Lauderia*
Occluded processes absent, valve surface has areolae?
Yes
Genus *Porosira*
Processes not on valve margin?
Yes
Genus *Minidiscus*


Genus *Thalassiosira*
Labiate process(es) near valve mantle; external tubes usually present?
Yes
Exactly one central or subcentral strutted process?
Yes
No
One marginal ring of strutted processes?
Yes
Beveled edge and in chains?
Yes
No
T. nordenskioeldii (10-50μm)
Cells in a cluster held together by mucus?
Yes
T.subtilis (15-32μm)
More than one central or subcentral strutted process?
Yes
No
Cluster of central strutted processes?
Yes
No
T. rotula (Coscinodiscus rotulus) (8-55μm)
Modified ring of subcentral strutted processes?
Yes
T. anguste-lineate (Coscinodiscus angustelineatus) (14-78μm)
No particular central or subcentral strutted process?
Yes
T.lentiginosa (Coscinodiscus lentiginosus var. lentiginosus) (47-95μm)

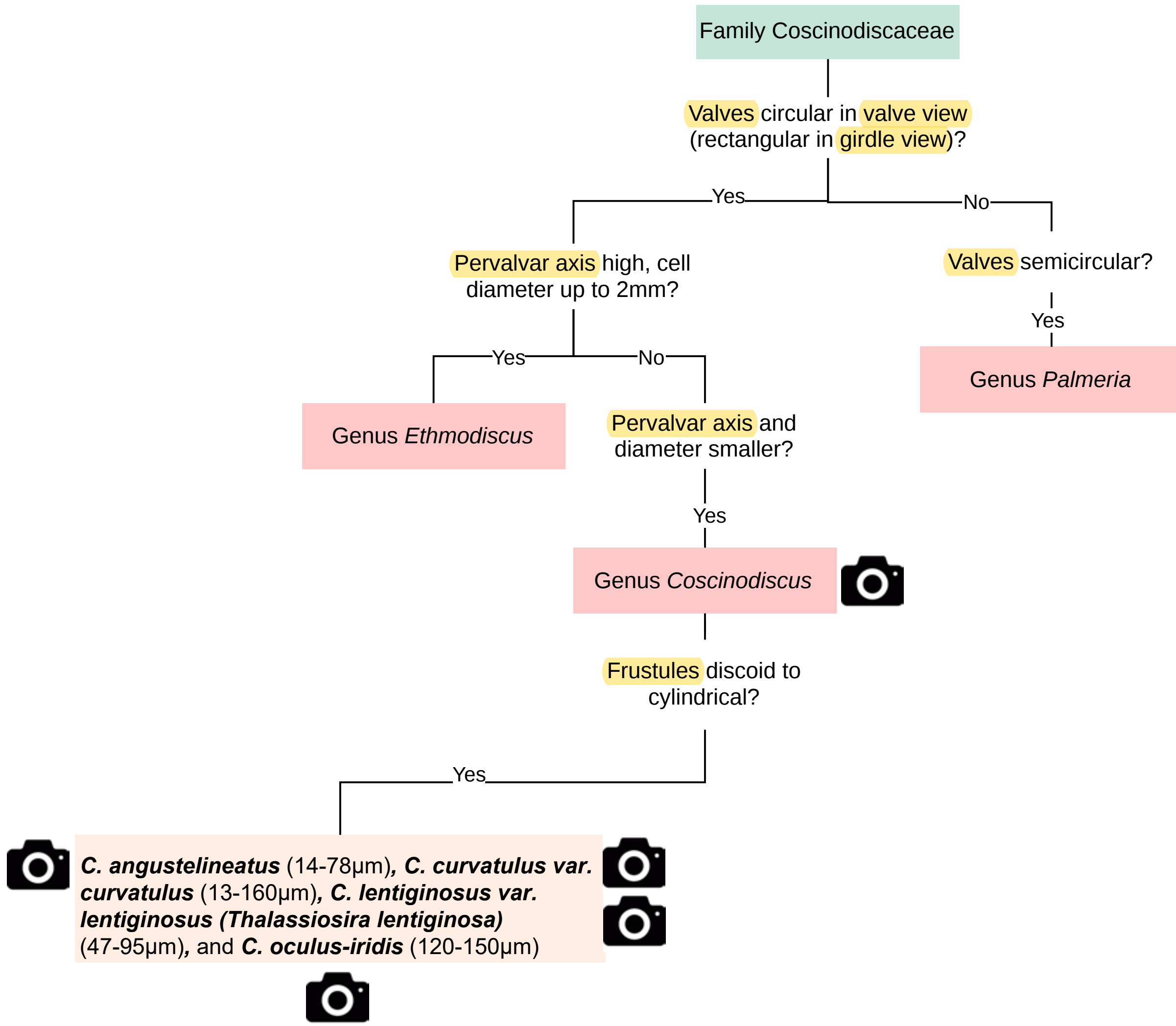

Family Melosiraceae
Cells close together in chains?
Yes
No
Cells in chains united by mucilage pads, sometimes also by a corona consisting of larger irregular spines; valve mantle high and strongly curved?
Cells separated by some distance in chains chains and are united by long external labiate processes?
Yes
No
Yes
Genus Melosira
go to p.13
Cells in chains united by interlocking ridges/grooves and marginal spines; valve mantle low and straight?
Genus Stephanopyxis
External structures of labiate processes joined midway between cells in chains?
Yes
Genus Paralia
Yes
Cells disk-shaped, small, short, thick-walled, with circular constrictions at each end; one girdle band usually covering the halves of two cells?
Same size areola on whole valve?
Yes
Yes
P. sulcata (Melosira sulcata) (8-130μm)
S.turris (36-57μm)

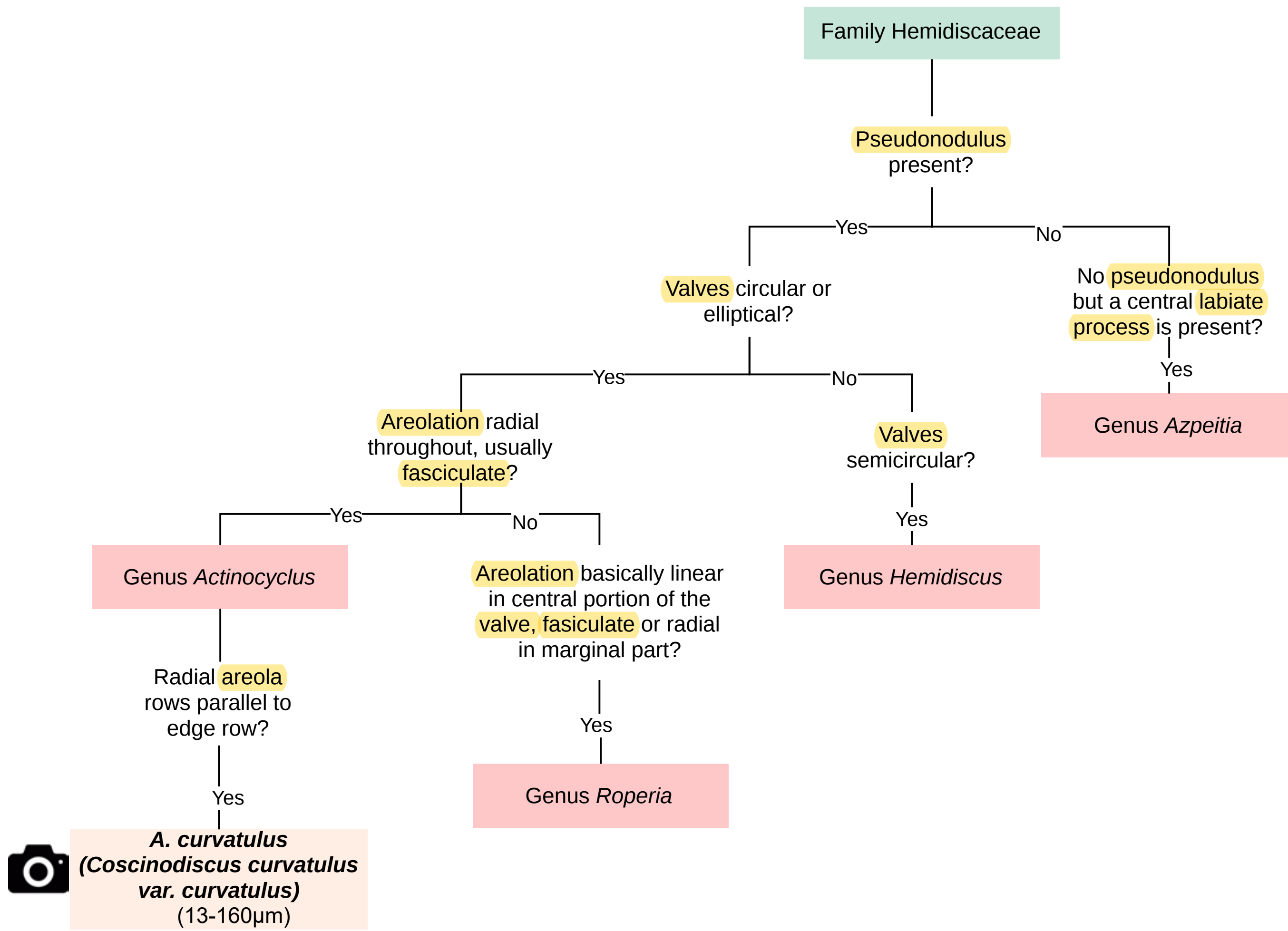

Genus *Melosira*
Valves and mantles usually lack ornamentation?
Yes
No
M.varians (13-22μm)
Cells cylindrical?
Yes
Most cells short (approximately <30 μm)?
Yes
Valves and gridle punctate with very convex and thick-walled valves; usually united in twos by girdle bands?
Yes
No
M. moniliformis (23-60μm)
Collar close to valve apex and no corona?
Yes
M. arctica var. arctica* (*M. arctica or ***Gaillonella arctica*)** (10-40μm)

Family Leptocylindraceae

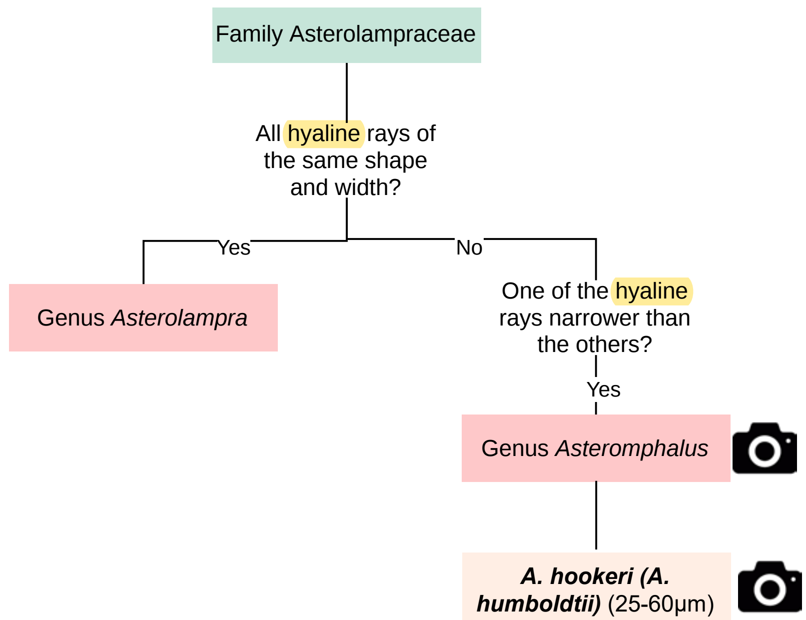
Marginal ring of spines, small, flap-like or triangular?

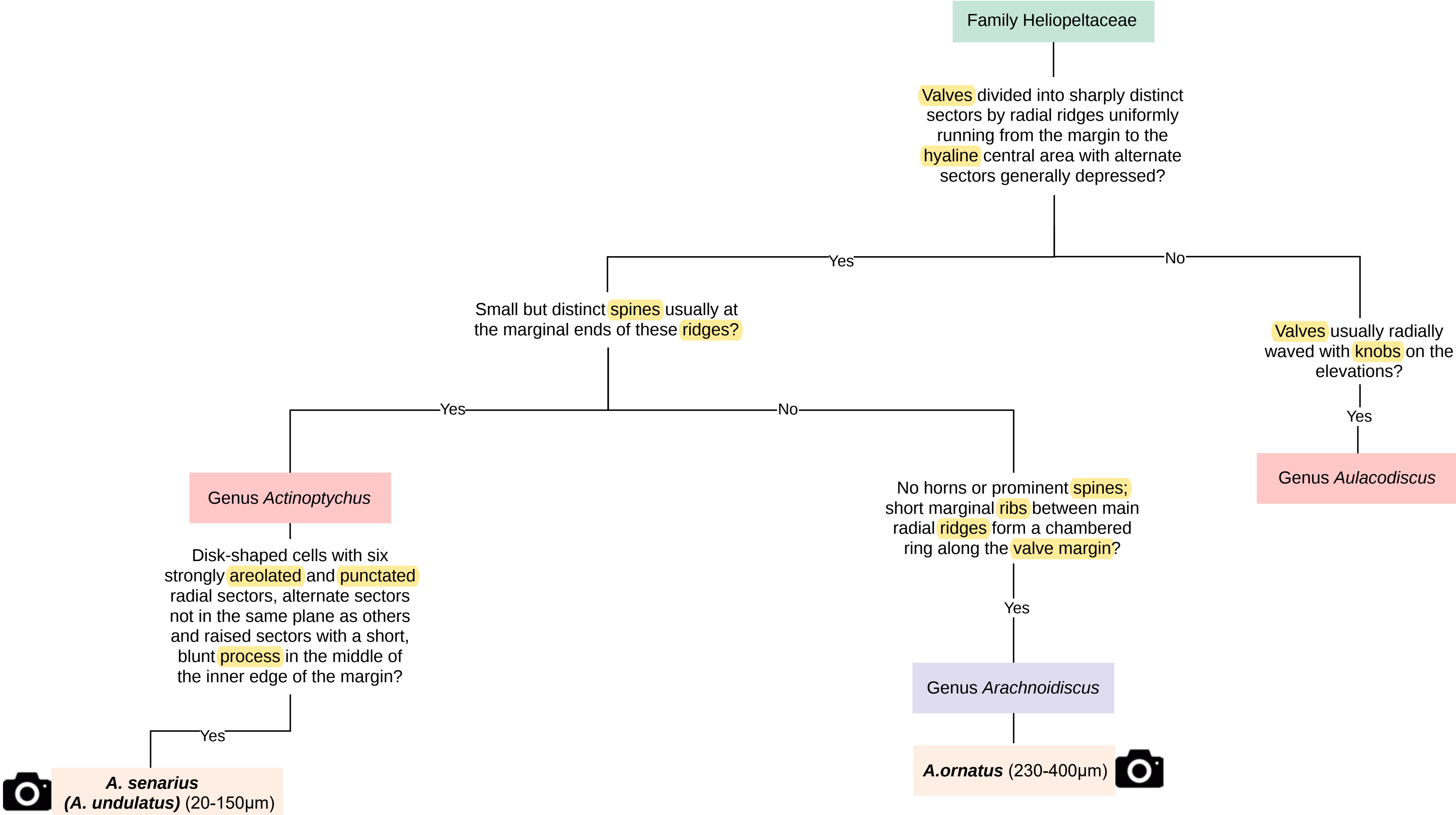
- **Yes** → Genus *Leptocylindrus*
  - Cell wall weakly silicified; numerous small rounded chloroplasts?
    - **Yes** → ***L.danicus*** (5-16µm)
- **No** → Marginal ring of long and uniquely-shaped spines?
  - **Yes** → Genus *Corethron*
    - Cells solitary and heterovalvate; valves with both hooked and long spines or long spines only; bands split with ligulae?
      - **Yes** → ***C.pennatum*** (pervalvar axis 20-240µm; apical axis 5-82µm) and ***C. hystrix*** (12-38µm)

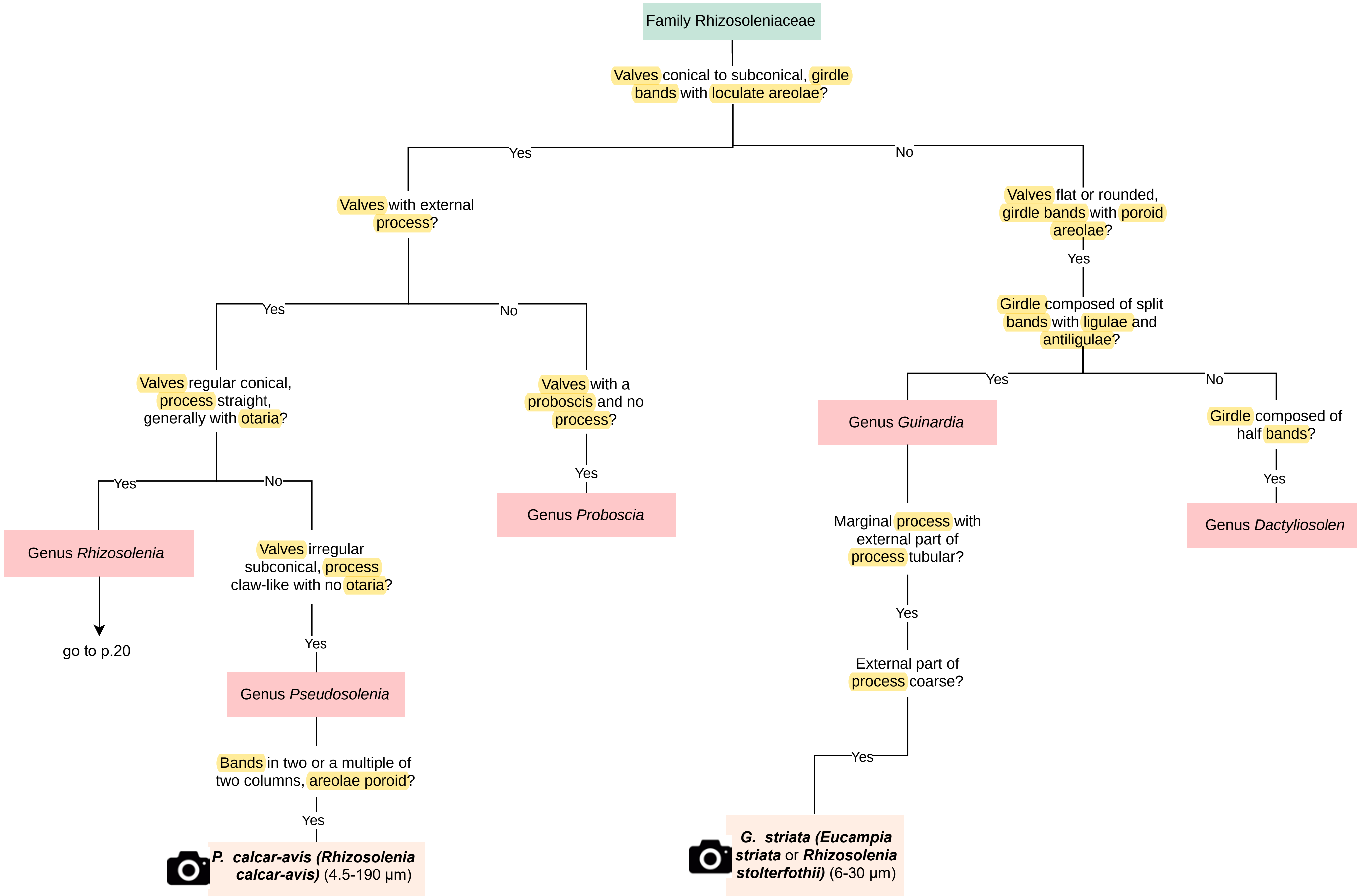

Family Coscinodiscaceae
Valves circular in valve view (rectangular in girdle view)?
Yes
No
Pervalvar axis high, cell diameter up to 2mm?
Valves semicircular?
Yes
Genus *Palmeria*
Yes
No
Genus *Ethmodiscus*
Pervalvar axis and diameter smaller?
Yes
Genus *Coscinodiscus*
Frustules discoid to cylindrical?
Yes
C. angustelineatus (14-78µm)***, C. curvatulus var. curvatulus*** (13-160µm)***, C. lentiginosus var. lentiginosus (Thalassiosira lentiginosa)*** (47-95µm)***,*** and ***C. oculus-iridis*** (120-150µm)

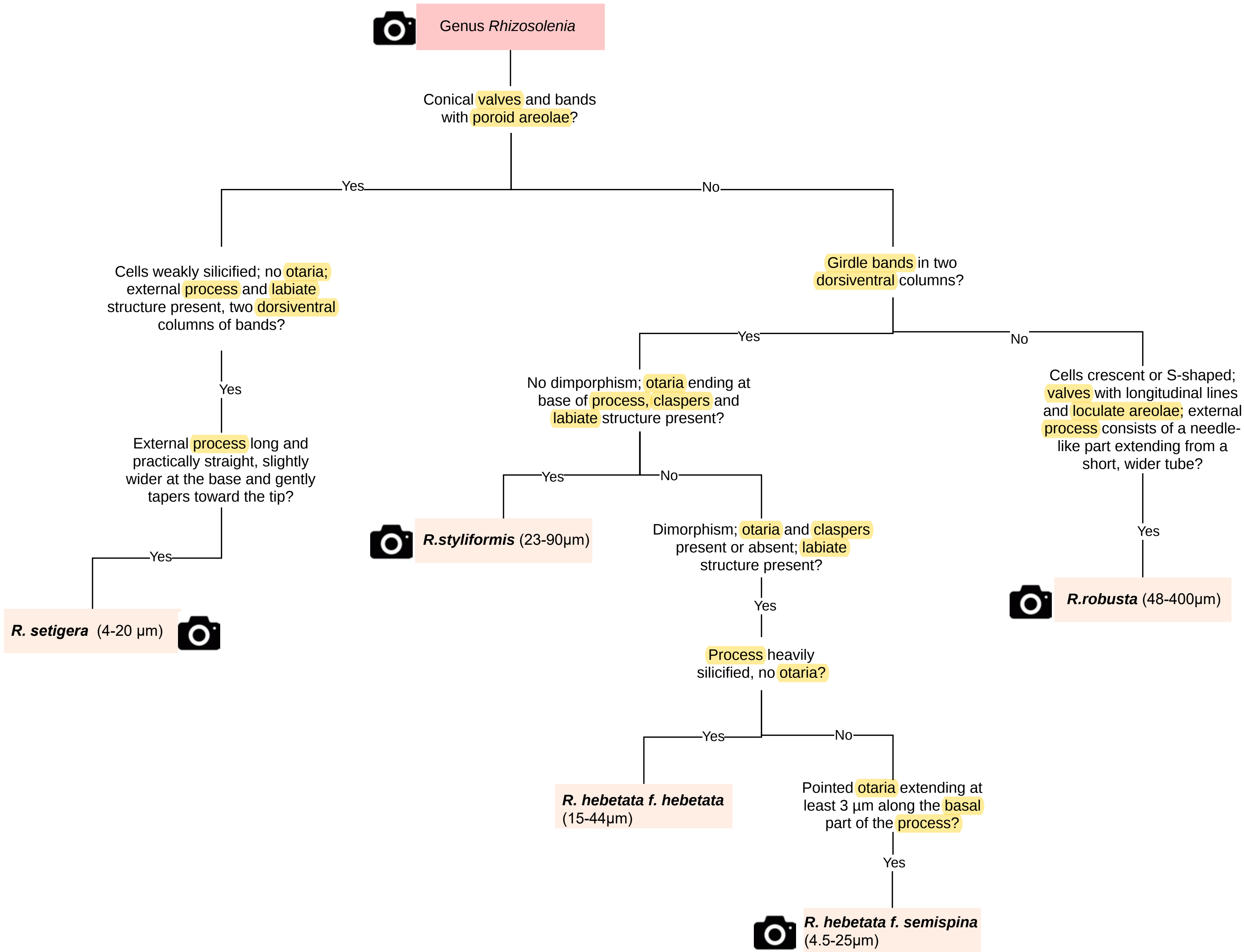


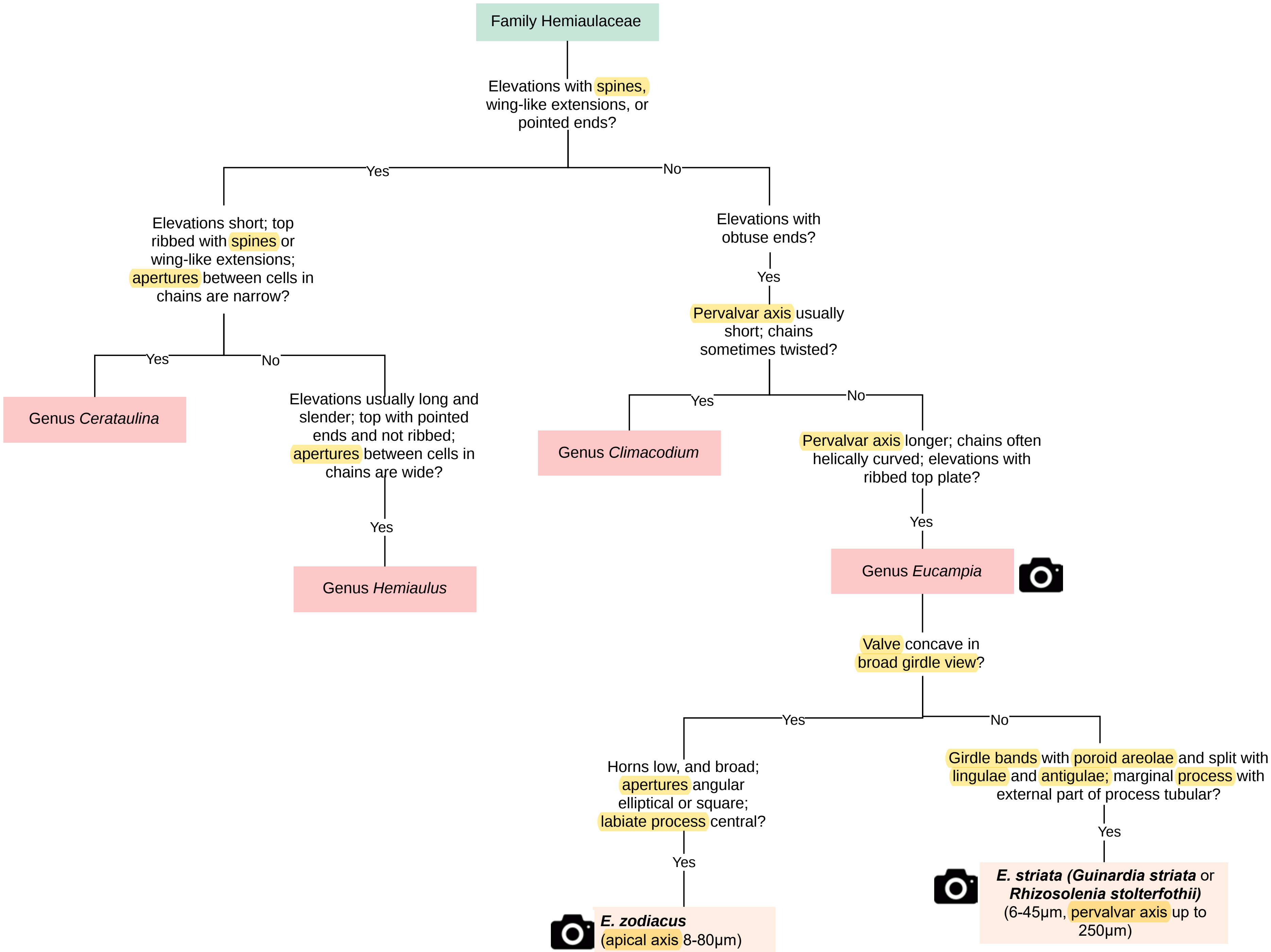
Family Hemidiscaceae
Pseudonodulus present?
Yes
No
Valves circular or elliptical?
No pseudonodulus but a central labiate process is present?
Yes
Genus *Azpeitia*
Yes
No
Areolation radial throughout, usually fasciculate?
Valves semicircular?
Yes
Genus *Hemidiscus*
Yes
No
Genus *Actinocyclus*
Areolation basically linear in central portion of the valve, fasciculate or radial in marginal part?
Yes
Genus *Roperia*
Radial areola rows parallel to edge row?
Yes
***A. curvatulus* (*Coscinodiscus curvatulus* var. *curvatulus*)**
(13-160µm)

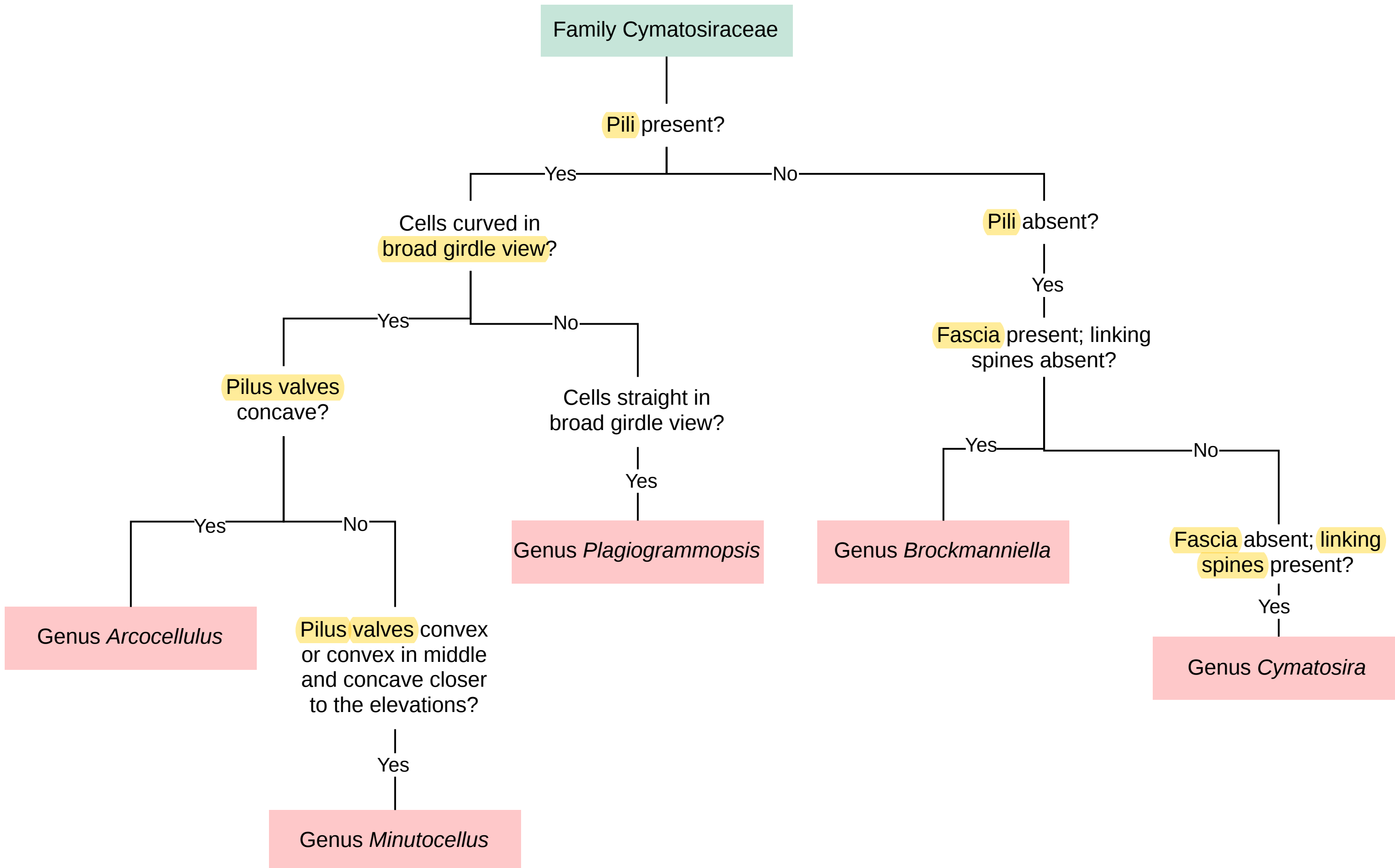

Family Asterolampraceae
All hyaline rays of the same shape and width?
Yes
No
Genus *Asterolampra*
One of the hyaline rays narrower than the others?
Yes
Genus *Asteromphalus*
A. hookeri (A. humboldtii) (25-60µm)

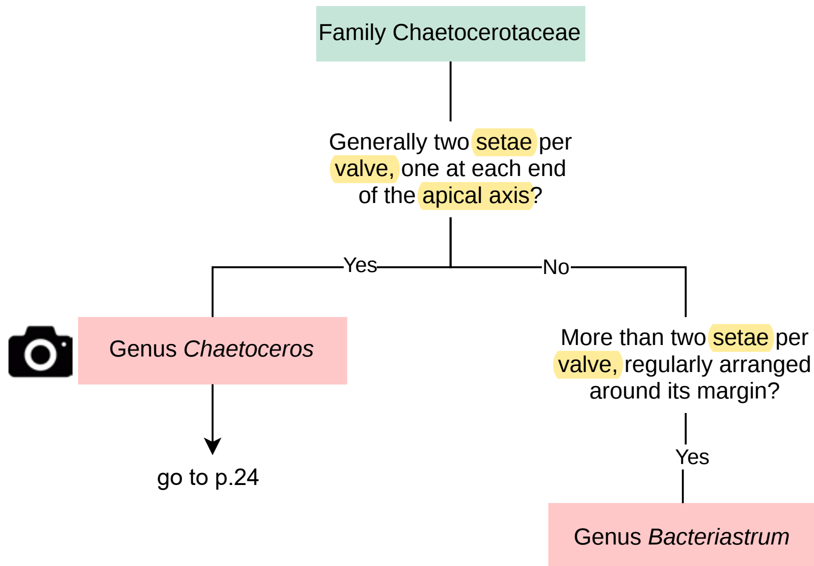

Family Heliopeltaceae
Valves divided into sharply distinct sectors by radial ridges uniformly running from the margin to the hyaline central area with alternate sectors generally depressed?
Yes
No
Small but distinct spines usually at the marginal ends of these ridges?
Valves usually radially waved with knobs on the elevations?
Yes
No
Yes
Genus *Aulacodiscus*
Genus *Actinoptychus*
No horns or prominent spines; short marginal ribs between main radial ridges form a chambered ring along the valve margin?
Disk-shaped cells with six strongly areolated and punctated radial sectors, alternate sectors not in the same plane as others and raised sectors with a short, blunt process in the middle of the inner edge of the margin?
Yes
Genus *Arachnoidiscus*
Yes
A.ornatus (230-400µm)
A. senarius
(A. undulatus) (20-150µm)

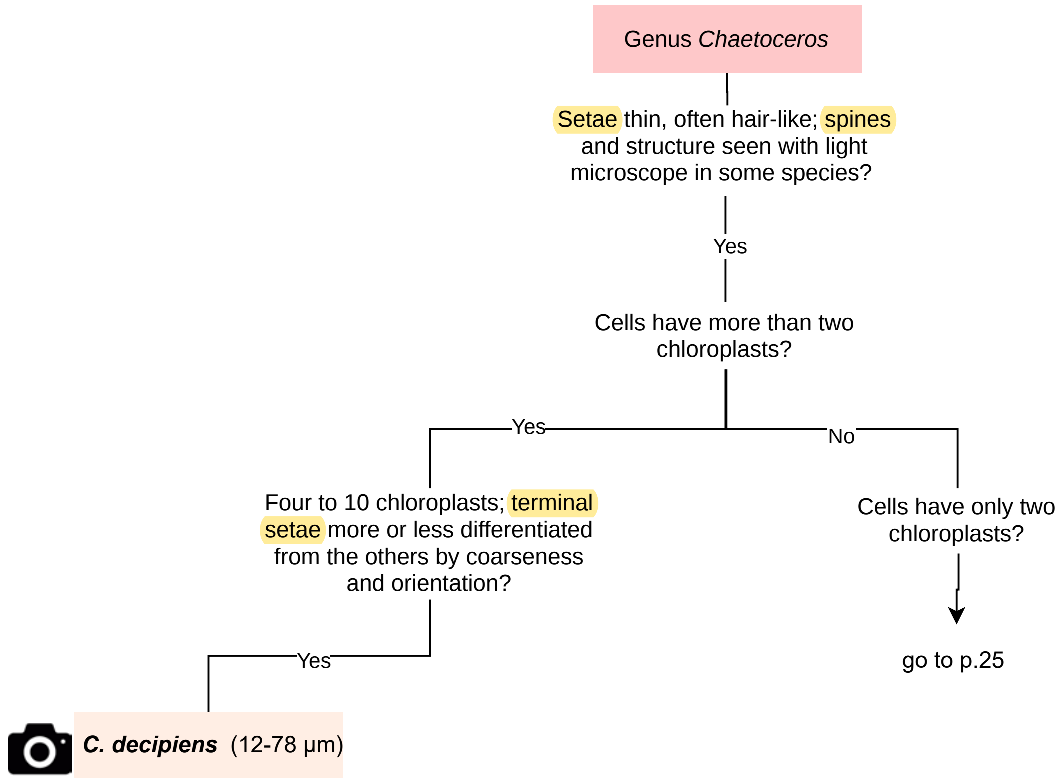

Family Rhizosoleniaceae
Valves conical to subconical, girdle bands with loculate areolae?
Yes
No
Valves with external process?
Yes
No
Valves regular conical, process straight, generally with otaria?
Yes
No
Genus *Rhizosolenia*
go to p.20
Valves irregular subconical, process claw-like with no otaria?
Yes
Genus *Pseudosolenia*
Bands in two or a multiple of two columns, areolae poroid?
Yes
P. calcar-avis (Rhizosolenia calcar-avis) (4.5-190 µm)
Valves with a proboscis and no process?
Yes
Genus *Proboscia*
Valves flat or rounded, girdle bands with poroid areolae?
Yes
Girdle composed of split bands with ligulae and antiligulae?
Yes
No
Genus *Guinardia*
Marginal process with external part of process tubular?
Yes
External part of process coarse?
Yes
G. striata (Eucampia striata or ***Rhizosolenia stolterfothii)*** (6-30 µm)
Girdle composed of half bands?
Yes
Genus *Dactyliosolen*

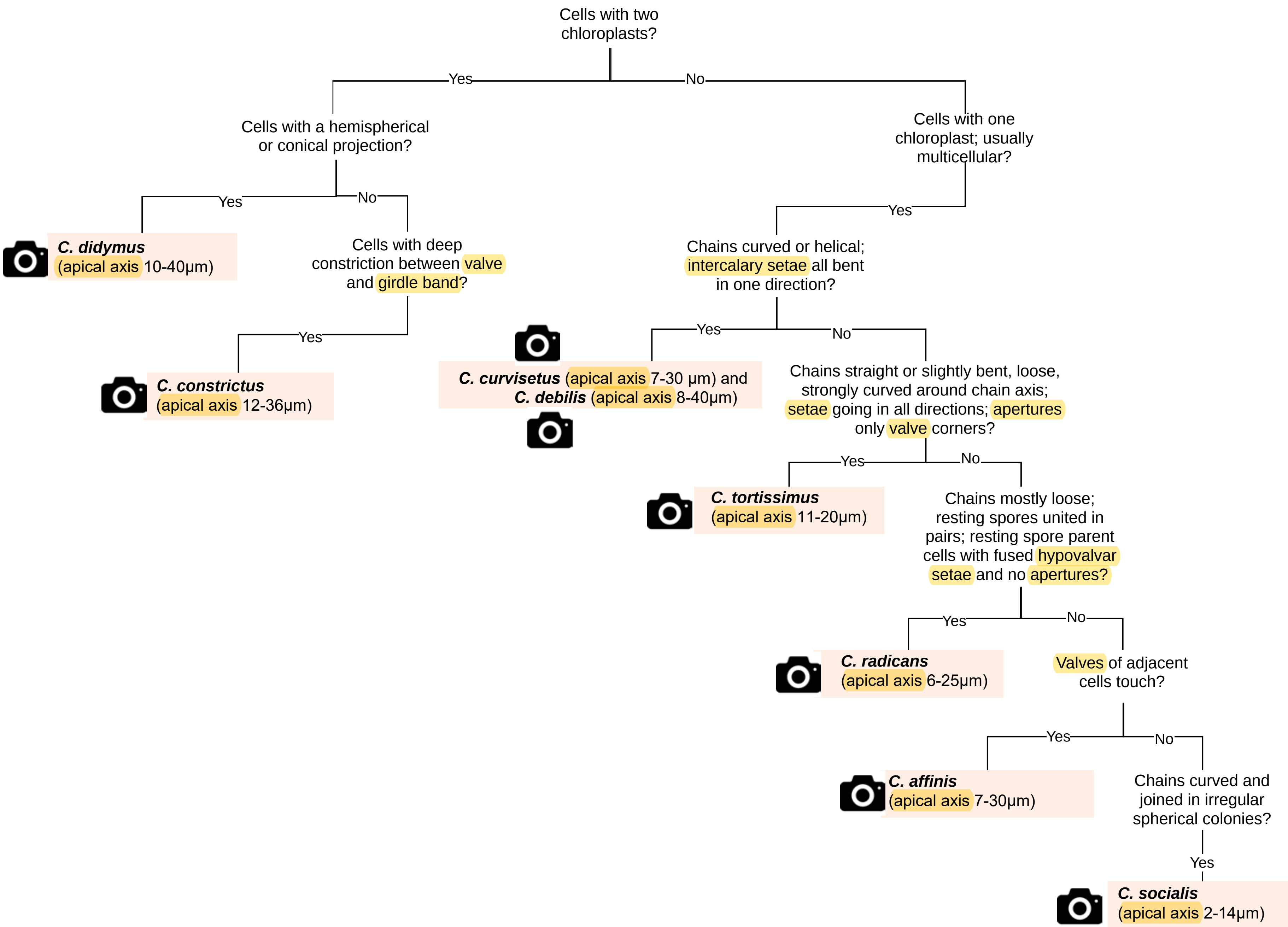

Genus *Rhizosolenia*
Conical valves and bands with poroid areolae?
Yes
No
Cells weakly silicified; no otaria; external process and labiate structure present, two dorsiventral columns of bands?
Yes
External process long and practically straight, slightly wider at the base and gently tapers toward the tip?
Yes
R. setigera (4-20 μm)
Girdle bands in two dorsiventral columns?
Yes
No
No dimporphism; otaria ending at base of process, claspers and labiate structure present?
Yes
No
R.styliformis (23-90μm)
Dimorphism; otaria and claspers present or absent; labiate structure present?
Yes
Process heavily silicified, no otaria?
Yes
No
R. hebetata f. hebetata (15-44μm)
Pointed otaria extending at least 3 μm along the basal part of the process?
Yes
R. hebetata f. semispina (4.5-25μm)
Cells crescent or S-shaped; valves with longitudinal lines and loculate areolae; external process consists of a needle-like part extending from a short, wider tube?
Yes
R.robusta (48-400μm)


Family Hemiaulaceae
Elevations with spines, wing-like extensions, or pointed ends?
Yes
No
Elevations short; top ribbed with spines or wing-like extensions; apertures between cells in chains are narrow?
Yes
Genus *Cerataulina*
No
Elevations usually long and slender; top with pointed ends and not ribbed; apertures between cells in chains are wide?
Yes
Genus *Hemiaulus*
Elevations with obtuse ends?
Yes
Pervalvar axis usually short; chains sometimes twisted?
Yes
Genus *Climacodium*
No
Pervalvar axis longer; chains often helically curved; elevations with ribbed top plate?
Yes
Genus *Eucampia*
Valve concave in broad girdle view?
Yes
Horns low, and broad; apertures angular elliptical or square; labiate process central?
Yes
E. zodiacus
(apical axis 8-80µm)
No
Girdle bands with poroid areolae and split with lingulae and antigulae; marginal process with external part of process tubular?
Yes
E. striata (Guinardia striata or ***Rhizosolenia stolterfothii)***
(6-45µm, pervalvar axis up to 250µm)

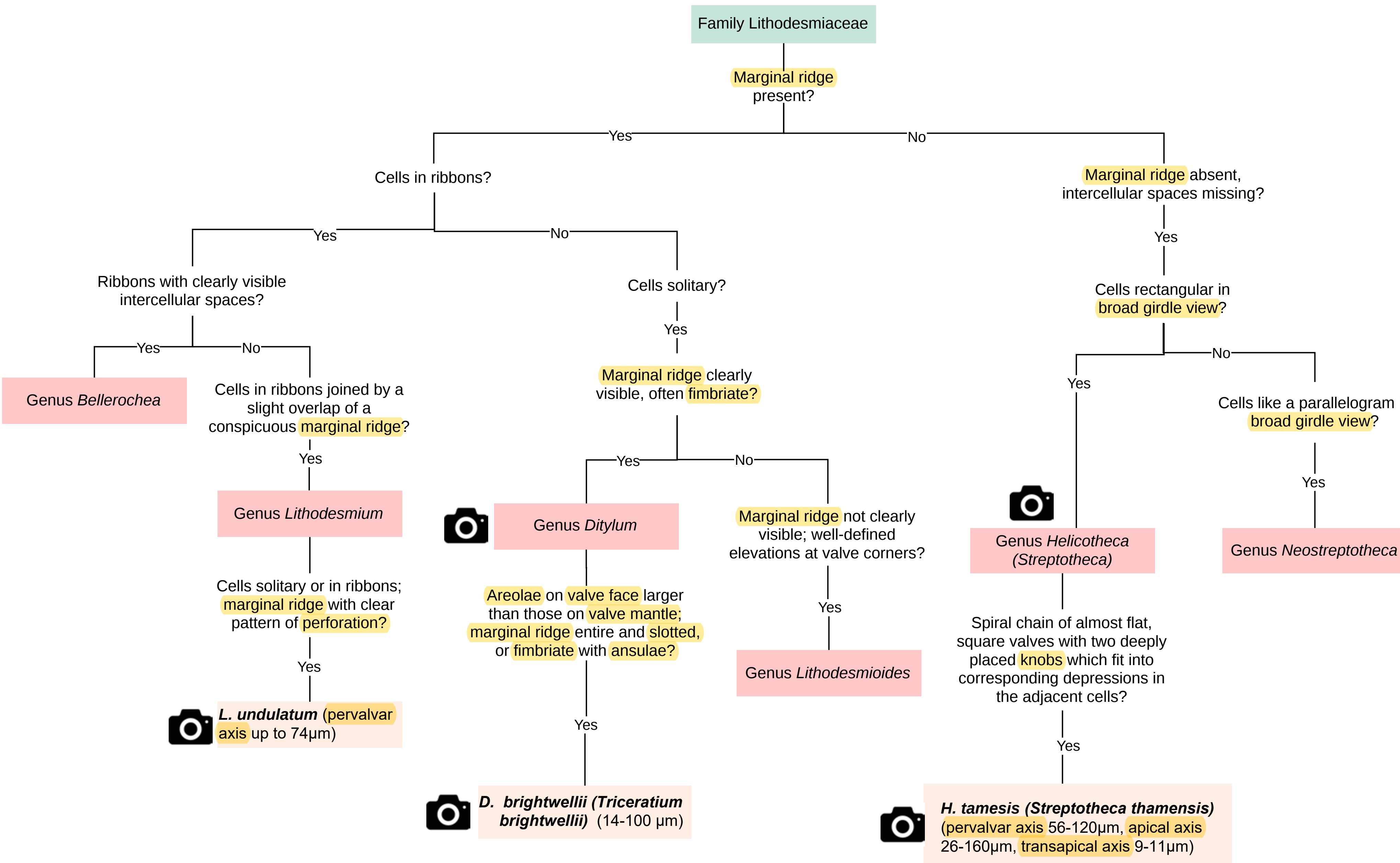

Family Cymatosiraceae
Pili present?
Yes
No
Cells curved in broad girdle view?
Pili absent?
Yes
No
Yes
Fascia present; linking spines absent?
Pilus valves concave?
Cells straight in broad girdle view?
Yes
Yes
No
Yes
No
Genus *Plagiogrammopsis*
Genus *Brockmanniella*
Fascia absent; linking spines present?
Yes
Genus *Arcocellulus*
Pilus valves convex or convex in middle and concave closer to the elevations?
Genus *Cymatosira*
Yes
Genus *Minutocellus*

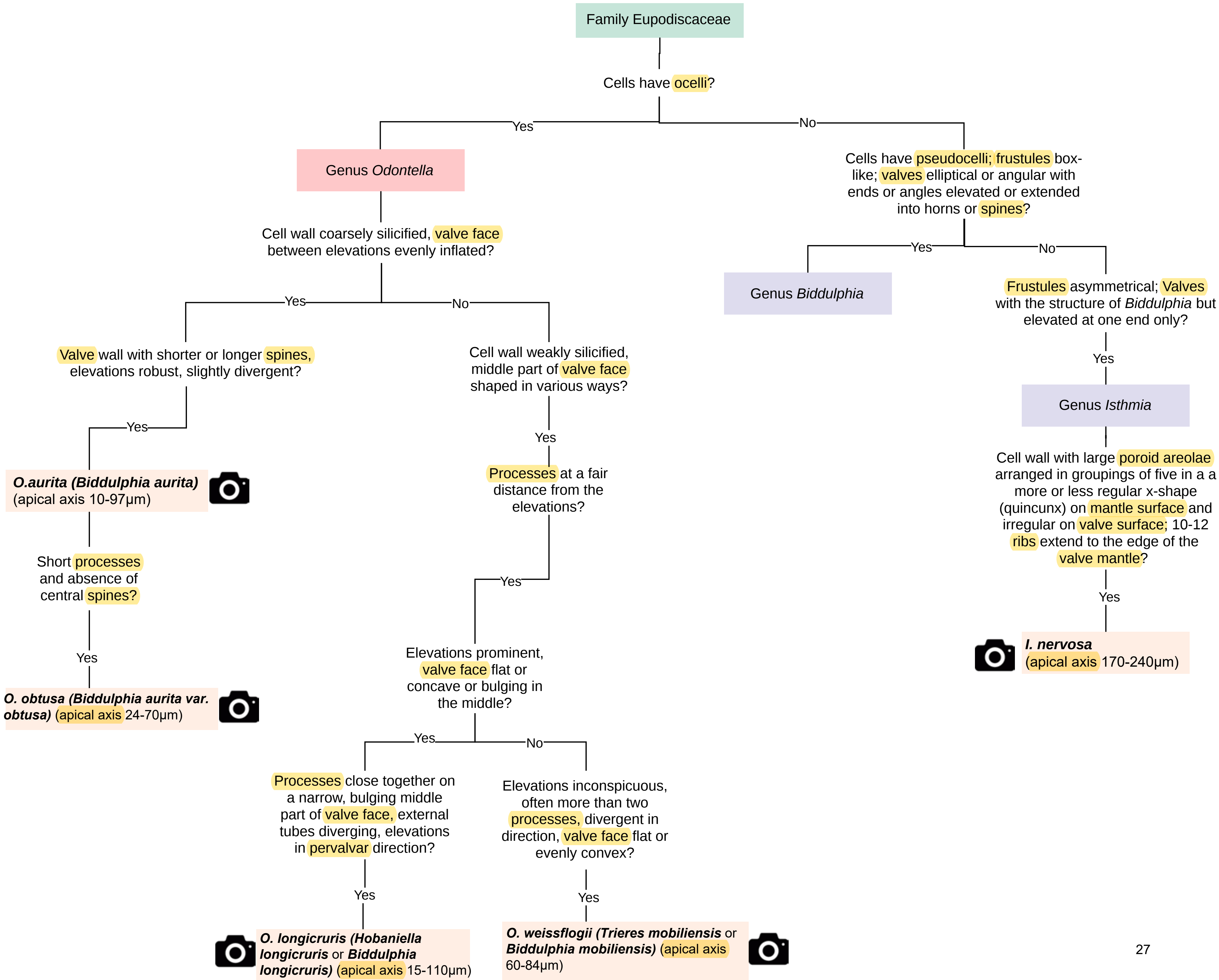

Family Chaetocerotaceae
Generally two setae per valve, one at each end of the apical axis?
Yes
No
Genus *Chaetoceros*
go to p.24
More than two setae per valve, regularly arranged around its margin?
Yes
Genus *Bacteriastrum*


Genus *Chaetoceros*
Setae thin, often hair-like; spines and structure seen with light microscope in some species?
Yes
Cells have more than two chloroplasts?
Yes
No
Four to 10 chloroplasts; terminal setae more or less differentiated from the others by coarseness and orientation?
Cells have only two chloroplasts?
go to p.25
Yes
C. decipiens (12-78 µm)

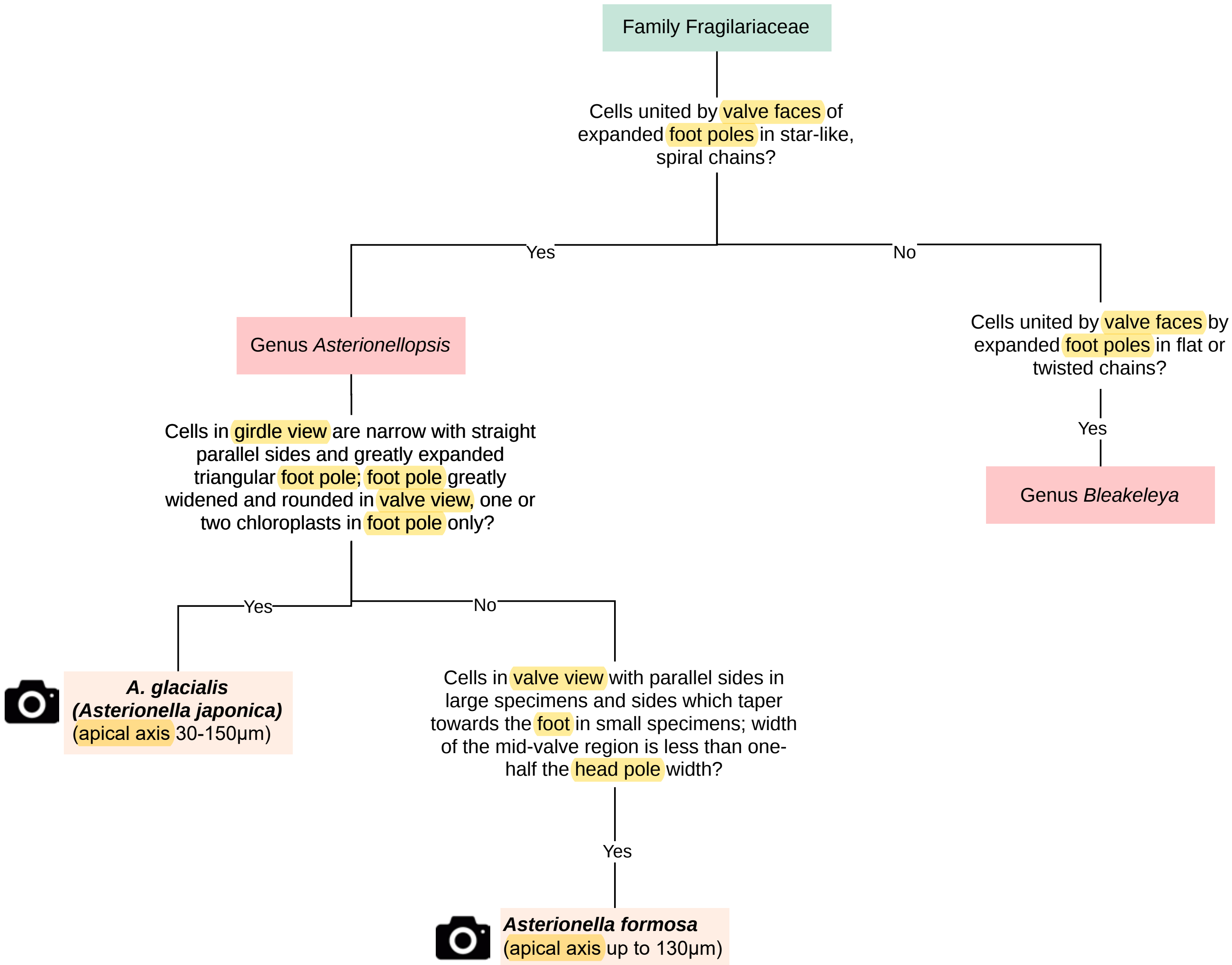


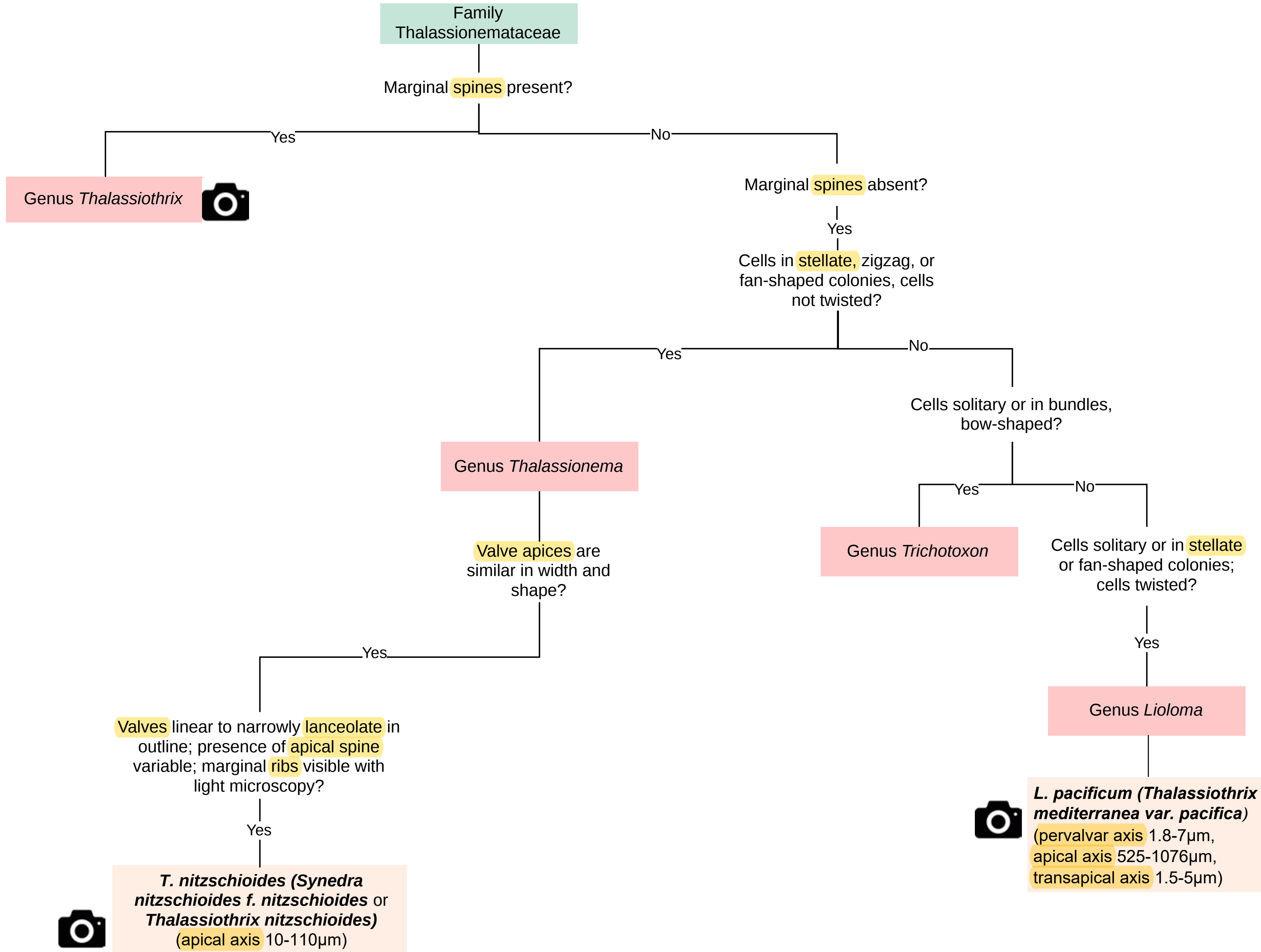
Cells with two chloroplasts?
Yes
No
Cells with a hemispherical or conical projection?
Yes
No
C. didymus (apical axis 10-40µm)
Cells with deep constriction between valve and girdle band?
Yes
C. constrictus (apical axis 12-36µm)
Cells with one chloroplast; usually multicellular?
Yes
Chains curved or helical; intercalary setae all bent in one direction?
Yes
No
C. curvisetus (apical axis 7-30 µm) and C. debilis (apical axis 8-40µm)
Chains straight or slightly bent, loose, strongly curved around chain axis; setae going in all directions; apertures only valve corners?
Yes
No
C. tortissimus (apical axis 11-20µm)
Chains mostly loose; resting spores united in pairs; resting spore parent cells with fused hypovalvar setae and no apertures?
Yes
No
C. radicans (apical axis 6-25µm)
Valves of adjacent cells touch?
Yes
No
C. affinis (apical axis 7-30µm)
Chains curved and joined in irregular spherical colonies?
Yes
C. socialis (apical axis 2-14µm)


Family Lithodesmiaceae
Marginal ridge present?
Yes
No
Cells in ribbons?
Marginal ridge absent, intercellular spaces missing?
Yes
No
Ribbons with clearly visible intercellular spaces?
Cells solitary?
Yes
Cells rectangular in broad girdle view?
Yes
No
Genus Bellerochea
Cells in ribbons joined by a slight overlap of a conspicuous marginal ridge?
Yes
Genus Lithodesmium
Cells solitary or in ribbons; marginal ridge with clear pattern of perforation?
Yes
L. undulatum (pervalvar axis up to 74µm)
Yes
Marginal ridge clearly visible, often fimbriate?
Yes
No
Genus Ditylum
Areolae on valve face larger than those on valve mantle; marginal ridge entire and slotted, or fimbriate with ansulae?
Yes
D. brightwellii (Triceratium brightwellii) (14-100 µm)
Marginal ridge not clearly visible; well-defined elevations at valve corners?
Yes
Genus Lithodesmioides
Yes
No
Genus Helicotheca (Streptotheca)
Spiral chain of almost flat, square valves with two deeply placed knobs which fit into corresponding depressions in the adjacent cells?
Yes
H. tamesis (Streptotheca thamensis) (pervalvar axis 56-120µm, apical axis 26-160µm, transapical axis 9-11µm)
Cells like a parallelogram in broad girdle view?
Yes
Genus Neostreptotheca



Family Eupodiscaceae
Cells have ocelli?
Yes
No
Genus *Odontella*
Cell wall coarsely silicified, valve face between elevations evenly inflated?
Yes
No
Valve wall with shorter or longer spines, elevations robust, slightly divergent?
Yes
O.aurita (Biddulphia aurita) (apical axis 10-97μm)
Short processes and absence of central spines?
Yes
O. obtusa (Biddulphia aurita var. obtusa) (apical axis 24-70μm)
Cell wall weakly silicified, middle part of valve face shaped in various ways?
Yes
Processes at a fair distance from the elevations?
Yes
Elevations prominent, valve face flat or concave or bulging in the middle?
Yes
No
Processes close together on a narrow, bulging middle part of valve face, external tubes diverging, elevations in pervalvar direction?
Yes
O. longicruris (Hobaniella longicruris or ***Biddulphia longicruris)*** (apical axis 15-110μm)
Elevations inconspicuous, often more than two processes, divergent in direction, valve face flat or evenly convex?
Yes
O. weissflogii (Trieres mobiliensis or ***Biddulphia mobiliensis)*** (apical axis 60-84μm)
Cells have pseudocelli; frustules box-like; valves elliptical or angular with ends or angles elevated or extended into horns or spines?
Yes
No
Genus *Biddulphia*
Frustules asymmetrical; Valves with the structure of *Biddulphia* but elevated at one end only?
Yes
Genus *Isthmia*
Cell wall with large poroid areolae arranged in groupings of five in a a more or less regular x-shape (quincunx) on mantle surface and irregular on valve surface; 10-12 ribs extend to the edge of the valve mantle?
Yes
I. nervosa (apical axis 170-240μm)


Family Fragilariaceae
Cells united by valve faces of expanded foot poles in star-like, spiral chains?
Yes
No
Genus *Asterionellopsis*
Cells united by valve faces by expanded foot poles in flat or twisted chains?
Yes
Genus *Bleakeleya*
Cells in girdle view are narrow with straight parallel sides and greatly expanded triangular foot pole; foot pole greatly widened and rounded in valve view, one or two chloroplasts in foot pole only?
Yes
No
A. glacialis (Asterionella japonica)
(apical axis 30-150µm)
Cells in valve view with parallel sides in large specimens and sides which taper towards the foot in small specimens; width of the mid-valve region is less than one-half the head pole width?
Yes
Asterionella formosa
(apical axis up to 130µm)

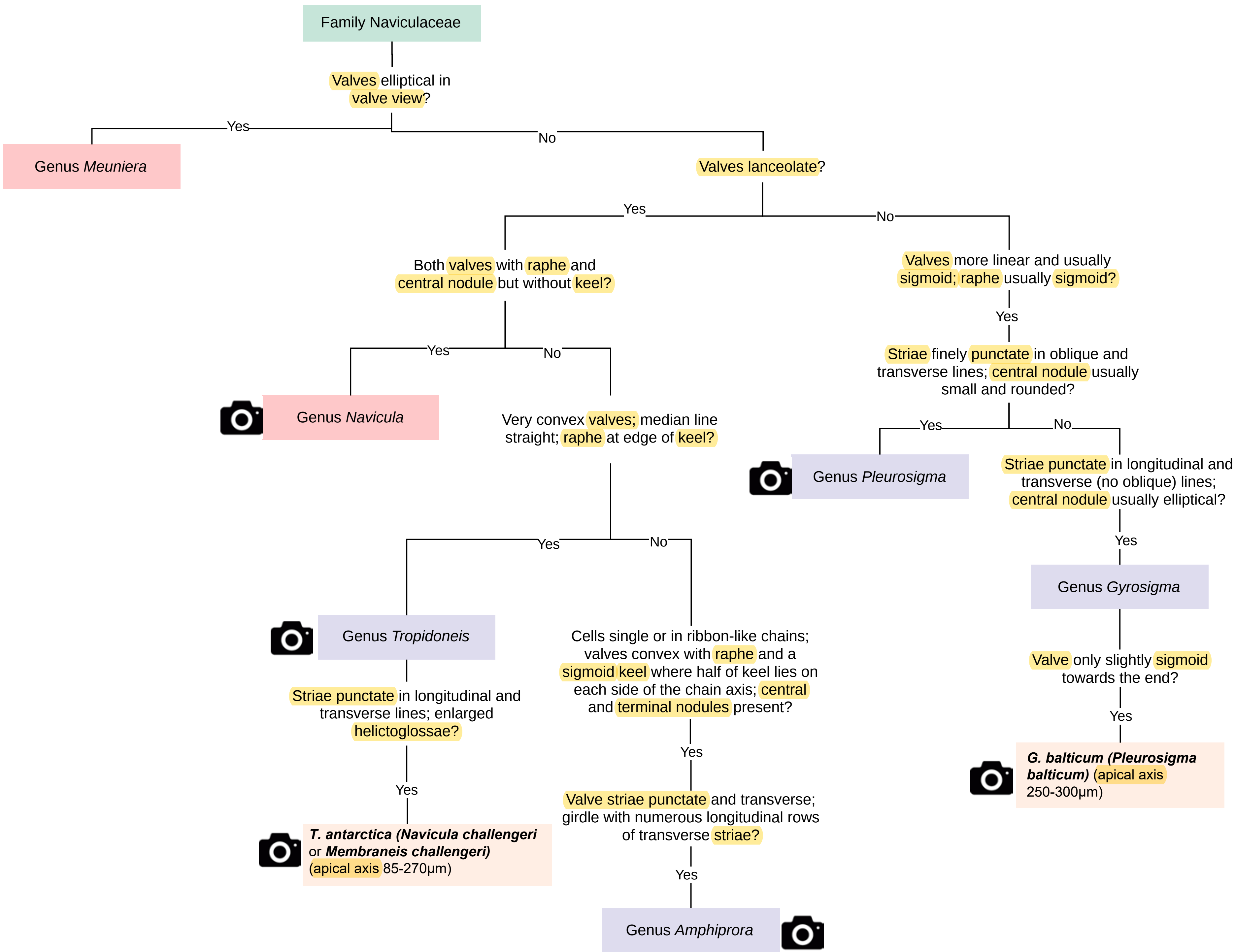

Family Thalassionemataceae
Marginal spines present?
Yes
No
Genus *Thalassiothrix*
Marginal spines absent?
Yes
Cells in stellate, zigzag, or fan-shaped colonies, cells not twisted?
Yes
No
Genus *Thalassionema*
Cells solitary or in bundles, bow-shaped?
Valve apices are similar in width and shape?
Yes
No
Genus *Trichotoxon*
Cells solitary or in stellate or fan-shaped colonies; cells twisted?
Yes
Yes
Genus *Lioloma*
Valves linear to narrowly lanceolate in outline; presence of apical spine variable; marginal ribs visible with light microscopy?
Yes
T. nitzschioides (Synedra nitzschioides f. nitzschioides or ***Thalassiothrix nitzschioides)*** (apical axis 10-110µm)
L. pacificum (Thalassiothrix mediterranea var. pacifica) (pervalvar axis 1.8-7µm, apical axis 525-1076µm, transapical axis 1.5-5µm)

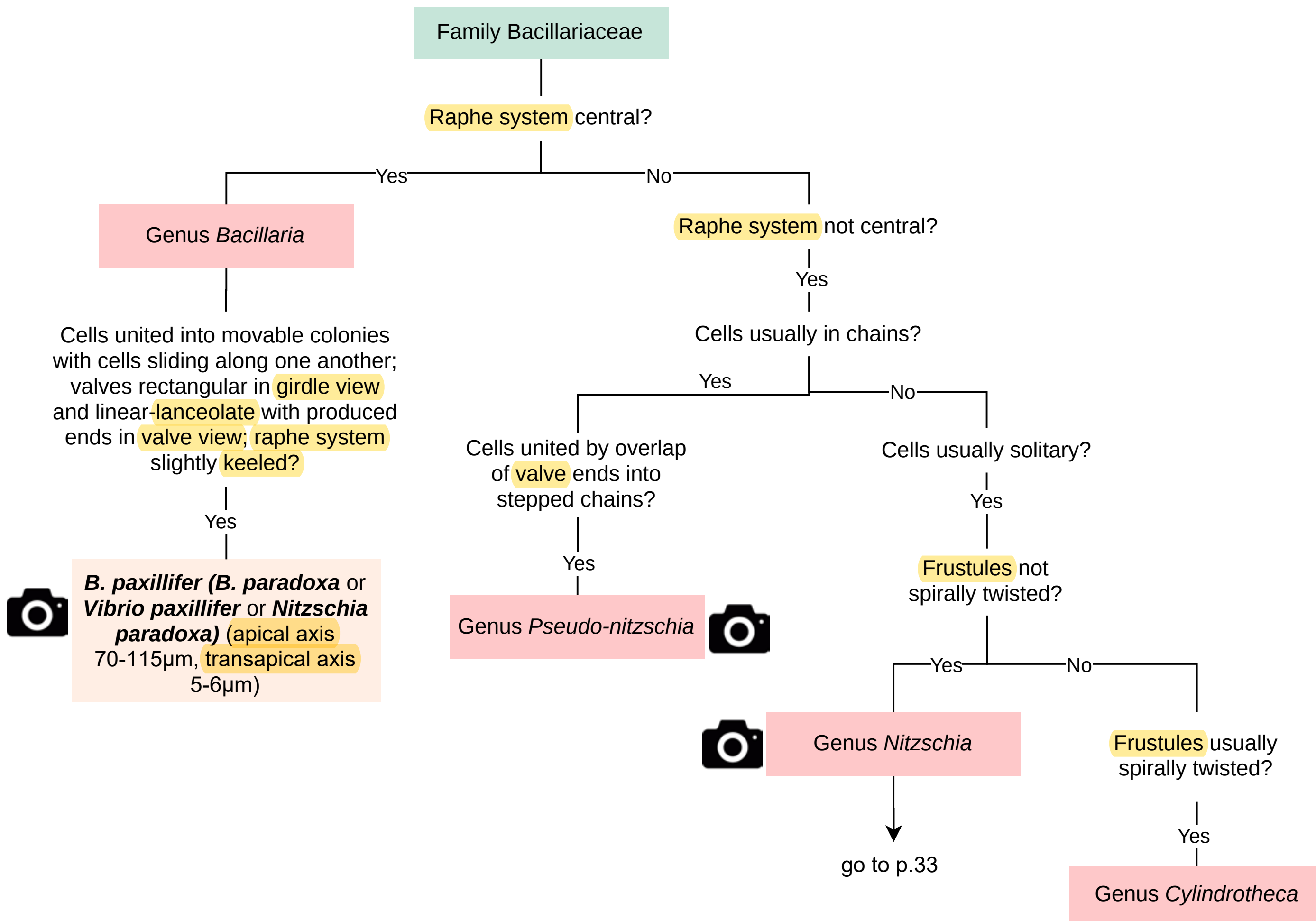
Family Achnanthaceae

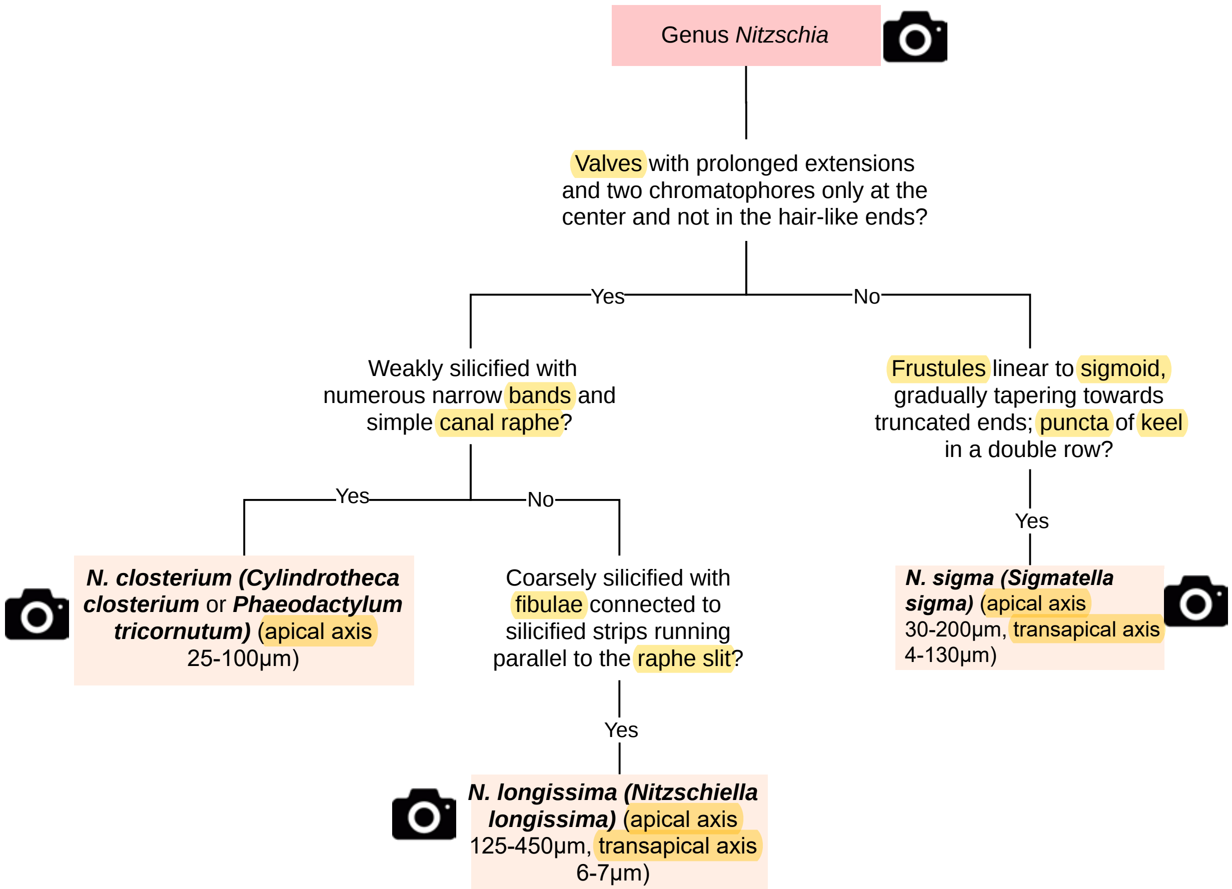
Heterovalvar cells; one valve has raphe with two longitudinal slits, and the other valve either does not have raphe or has short slits?

Yes

Genus *Achnanthes*


Family Naviculaceae
Valves elliptical in valve view?
Yes
Genus *Meuniera*
No
Valves lanceolate?
Yes
Both valves with raphe and central nodule but without keel?
Yes
Genus *Navicula*
No
Very convex valves; median line straight; raphe at edge of keel?
Yes
Genus *Tropidoneis*
Striae punctate in longitudinal and transverse lines; enlarged helictoglossae?
Yes
T. antarctica (Navicula challengeri or ***Membraneis challengeri)*** (apical axis 85-270µm)
No
Cells single or in ribbon-like chains; valves convex with raphe and a sigmoid keel where half of keel lies on each side of the chain axis; central and terminal nodules present?
Yes
Valve striae punctate and transverse; girdle with numerous longitudinal rows of transverse striae?
Yes
Genus *Amphiprora*
No
Valves more linear and usually sigmoid; raphe usually sigmoid?
Yes
Striae finely punctate in oblique and transverse lines; central nodule usually small and rounded?
Yes
Genus *Pleurosigma*
No
Striae punctate in longitudinal and transverse (no oblique) lines; central nodule usually elliptical?
Yes
Genus *Gyrosigma*
Valve only slightly sigmoid towards the end?
Yes
G. balticum (Pleurosigma balticum) (apical axis 250-300µm)


Family Bacillariaceae
Raphe system central?
Yes
No
Genus *Bacillaria*
Cells united into movable colonies with cells sliding along one another; valves rectangular in girdle view and linear-lanceolate with produced ends in valve view; raphe system slightly keeled?
Yes
B. paxillifer (B. paradoxa or ***Vibrio paxillifer*** or ***Nitzschia paradoxa)*** (apical axis 70-115µm, transapical axis 5-6µm)
Raphe system not central?
Yes
Cells usually in chains?
Yes
No
Cells united by overlap of valve ends into stepped chains?
Yes
Genus *Pseudo-nitzschia*
Cells usually solitary?
Yes
Frustules not spirally twisted?
Yes
No
Genus *Nitzschia*
go to p.33
Frustules usually spirally twisted?
Yes
Genus *Cylindrotheca*


Genus *Nitzschia*
Valves with prolonged extensions and two chromatophores only at the center and not in the hair-like ends?
Yes
No
Weakly silicified with numerous narrow bands and simple canal raphe?
Frustules linear to sigmoid, gradually tapering towards truncated ends; puncta of keel in a double row?
Yes
No
Yes
N. closterium (Cylindrotheca closterium or ***Phaeodactylum tricornutum)*** (apical axis 25-100µm)
Coarsely silicified with fibulae connected to silicified strips running parallel to the raphe slit?
N. sigma (Sigmatella sigma) (apical axis 30-200µm, transapical axis 4-130µm)
Yes
N. longissima (Nitzschiella longissima) (apical axis 125-450µm, transapical axis 6-7µm)

Common Terminology for Diatom Morphology

Annulus	central ring without areolae in centric diatoms (Tomas et al. 1997)
Araphid	refers to a cell that lacks a raphe system
Alveolus / Alveoli (plural)	elongated chambers that have an external wall with fine pores and forms striae (https://diatoms.org/glossary)
Areola / Areolae (plural)	regularly repeated pores (Ross et al. 1979, Simonsen 1975) **Loculate:** refers to chamber-like areolae with a velum (perforated layer of silica) as one wall and a foramen or an opening on the wall opposite the velum **Poroid**: refers to areolae that is not constricted by a foramen
Basal	referring to the bottom layer, typically of a membrane or cell wall
Bipolar	refers to symmetry in which two structures are present on each end of the cell
Frustule	silica parts of a diatom cell wall composed of two thecae/valves and the girdle (Ross et al. 1979)
Girdle	part of a frustule between the valves, made up of two cingulum (the epicingula is the part of the girdle associated with the epitheca and the hypocingula is the part of the valve associated with the hypotheca) Girdle bands: single elements of the girdle that make up the cingulum (Tomas et al. 1997)
Hyaline	part of the valve that lacks areolae or other ornamentation (Ross et al. 1979)
Hypovalvar	refers to the smaller valve of a frustule
Intercalary	between cells
Intercellular space	space between cells
Isopolar	refers to (pennate) valves that are symmetric to the transapical axis and have similar sized and shaped poles, as opposed to **heteropolar** where the valve is asymmetric adn the poles have different shapes (https://diatoms.org/glossary)
Lanceolate	refers to a valve shape that is elongated with tapered ends, similar to the shape of a rice grain
Marginal ridge	a ridge located between the valve face and mantle (Simonsen 1975)
Ornamentation	Pores or other structures on the valve
Processes	silica projections (Ross et al. 1979, Simonsen 1975) **Labiate / rimoportula:** a process that goes through the valve and appears as a tube on the external valve face and as a pair of lips on the internal valve face **Strutted / fultoportula:** a tube-like process that appears as either a tube or a pore on the external valve face and is surrounded by 2-5 pores (called satellite pores) which are visible in the internal valve face **Occluded:** a process that appears as a tube on the external valve face but closed off on the internal valve face
Puncta	Small areolae; a cell with many puncta is said to be **punctate** (Ross et al. 1979)
Raphe / Raphe fins	one or two slits through the valve wall (Ross et al. 1975)
Raphid	refers to a cell that has a raphe system
Spine	short, pointed silica extension resembling the shape of a slightly curved spike; may be called a **spinule** if very small, a **granule** if more rounded, or a **linking spine** if they connect frustules together in a chain (Simonsen 1975)
Sternum	longitudinal silica element in pennate diatoms that usually has few or lacks areolae (Tomas et al. 1997)
Striae	rows of areolae or alveoli (Ross et al. 1979, Simonsen 1975)
Theca	includes the valve and its cingulum (see **Girdle**); the epitheca is composed of the epivalve and the epicingulum, the hypotheca is composed of the hypovalve and the hypocingulum (Ross et al. 1979)
Undulate	refers to a wave-like shape of a valve
Unipolar	refers to symmetry in which one structure is present on one end of the cell
Valve	one of two diatom cell wall plates made of silica; the larger valve (epivalve) fits over top of the smaller valve (hypovalve), resembling the appearance of a petri dish (Ross et al. 1979)
Valve apex	refers to the poles of a pennate valve
Valve face	part of valve surrounded by mantle and is most visible when a frustule is in valve view (Ross et al. 1979, Simonsen 1975); resembles the flat side of a petri dish
Valve mantle	side of the valve that surrounds the valve face and is visible when a frustule is in girdle view (Ross et al. 1979, Simonsen 1975); resembles the walls of a petri dish
Valve margins	outer edge of the valve face just before the mantle

Axes and Orientation Terminology for Diatom Morphology

Axes	**Pervalvar axis**	perpendicular axis through the center of the valve faces (Tomas et al. 1997)
	Apical axis	longer axis along the midline of the valve face (https://diatoms.org/glossary)
	Transapical axis	shorter axis on the valve face that is perpendicular to the apical axis
	Dorsiventral	refers to the axis which joins the dorsal or more arched side and ventral side of an asymmetrical pennate valve (https://diatoms.org/glossary)
View Orientations	**Valve view**	frustule is oriented such that the face is most visible; centric diatoms appear as circles in valve view
	Internal valve view	considering a valve resembles one side of a petri dish, this view orients the "dish" to the viewer like looking into a bowl
	External valve view	considering a valve resembles one side of a petri dish, this view orients the "dish" to the viewer like looking at the top of a dome
	Girdle view	frustule is oriented such that the mantle and girdle bands are most visible; under light microscopy, centric diatoms may appear as rectangles in girdle view

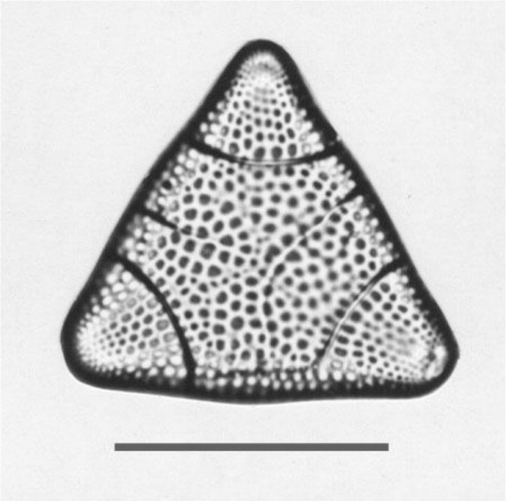
Diatom Family Specific Terminology

	Ribs	solid structures made of silica (https://diatoms.org/glossary)
Thalassiosiraceae	**Mucilage**	gelatinous substance produced by the cell **Mucilage pads:** area of mucilage that accumulates on the cell
	Collar	membraneous extension on the outer edge of a valve (Simonsen 1975), resembling the brim of a floppy/bucket hat
Melosiraceae	**Corona**	large irregular spines arranged in a ring at the valve apex (Tomas et al. 1997)
	Heterovalvate	refers to frustules in which one valve differs morphologically from the other valve (https://diatoms.org/glossary)
Leptocylindraceae	**Ligulae and Antiligulae**	silica projections that extend from split girdle bands, often filling the split; cells with ligulae/antiligulae are referred to as **ligulate** (Tomas et al. 1997, https://diatoms.org/glossary)
Coscinodiscaceae	**Discoid**	refers to the shape of a cell that is disk-llike with a indentation in the center, resembling the shape of a red blood cell
	Fasiculation / Fasciculate	bundles or groupings of striae, where each bundle is referred to as a **fascicle** (Tomas et al. 1997, Ross et al. 1979)
Hemidiscaceae	**Pseudonodulus**	a single structure located near the margin of the valve and may appear as a larger open pore under light microscopy (Tomas et al. 1997)
Heliopeltaceae	**Knobs**	rounded silica ornaments on the valve surface
	Claspers	membranous structures often connecting to the marginal ridges of the adjacent valve in linked cells (Tomas et al. 1997)
	Conical	cone-like shape
	Otarium / Otaria (plural)	costae located at or near the base of an external process (Tomas et al. 1997)
	Proboscis	elongated part of the valve with a tip that looks cut short and can fit into a groove in an adjacent valve in linked cells (Tomas et al. 1997)
Rhizosoleniaceae	**Subconical**	somewhat cone-like shape
Hemiaulaceae	**Aperture**	opening between valves (Simonsen 1975)
	Fascia	hyaline band that extends on the transapical axis of a pennate diatom (Tomas et al. 1997)
Cymatosiraceae	**Pilus / Pili (plural)**	long hairs (Tomas et al. 1997)
	Costa / Costae (plural)	thickened and elongated part of the valve that lacks ornamentation, often seen in pennate diatoms (Ross et al. 1979, Simonsen 1975))
Chaetocerotaceae	**Seta / Setae (plural)**	hollow extension coming from the valve margin that appear as very elongated spines (https://diatoms.org/glossary) **Terminal setae**: setae on the end cells of a chain (Simonsen 1975)
	Ansula / Ansulae (plural)	fringes on the marginal ridge of *Ditylum* that are shaped like ribbons which have been split down the middle longitudinally (Tomas et al. 1997)
	Fimbriate	refers to a marginal ridge that has **ansulae**
	Perforation	small holes typically in a row, in reference to **areola** (Ross et al. 1979)
Lithodesmiaceae	**Slotted**	refers to a marginal ridge that has a perforated basal membrane (Tomas et al. 1997)
	Foot pole (basal pole)	broader end of a pennate diatom (Tomas et al. 1997, https://diatoms.org/glossary)
Fragilriaceae	**Head pole (apical pooe)**	narrower end of a pennate diatom (Tomas et al. 1997, https://diatoms.org/glossary)
Thalassionemataceae	**Stellate**	star-like arrangement of cells in a colony where cells radiate from a central point (https://diatoms.org/glossary)
Achnanthaceae	**Knot stauroid**	refers to a central stauros with a slightly more pronounced central nodule

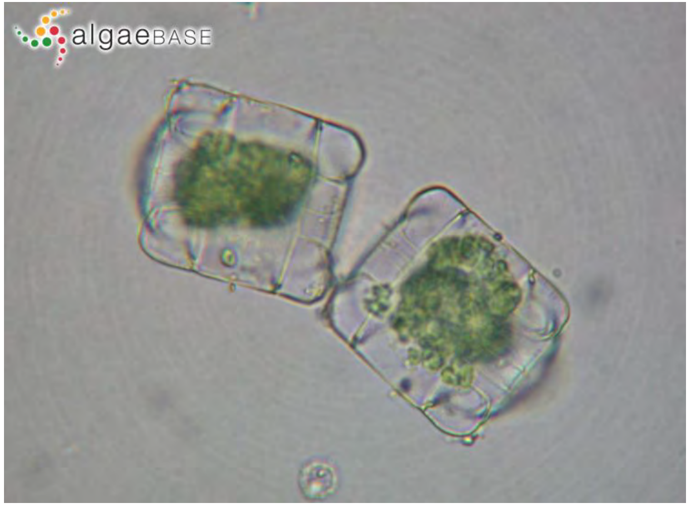
	Central nodule	thicker hyaline silica separating raphe slits (Tomas et al. 1997)
	Helictoglossa / Helictoglossae (plural)	internal silica thickening at the end of a raphe in the shape of lips or a rolled tongue (https://diatoms.org/glossary)
	Pyrenoid	functional cell structure used for carbon dioxide fixation, usually difficult to distinguish with light microscopy (https://diatoms.org/glossary)
	Rostrate	refers to a valve apex on a pennate diatom with a beak-like shape, as opposed to **capitate** with a rounded knob-like shape (https://diatoms.org/glossary)
	Stauros	thicker hyaline silica extending from the central nodule to the valve margins and separating the raphe slits (Tomas et al. 1997, https://diatoms.org/glossary)
Naviculaceae	**Subacute ends**	refers to a valve apices on a pennate diatom that are tapered and slightly acute in shape
	Canal raphe	"space on the inner side of the raphe" (Ross et al. 1979)
	Fibula / Fibulae (plural)	internal silica structures that extend from the valve face to support either side of the raphe in pennate diatoms (Tomas et al. 1997, https://diatoms.org/glossary)
	Interstriae	space between striae that does not have pores (Tomas et al. 1997)
	Keeled	thickened and elevated silica on the valve that contains raphe (Simonsen 1975)
	Produced end	refers to a valve apex on a pennate diatom with with a slightly rounded knob-like shape but not quite capitate (see **Rostrate**)
Bacillariaceae	**Sigmoid**	curved, S-like shape; usually in reference to pennate diatoms

Diatom Photo Gallery

Triceratium sp.
(LM, valve view)



Triceratium alternans
Synonyms: *Trigonium alternans, Biddulphia alternans*
(LM, valve view,
image by S.R. Stidolph)

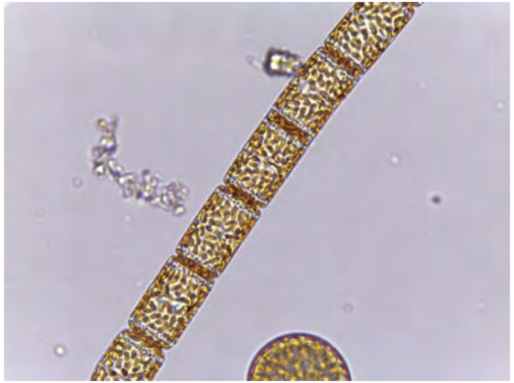


Triceratium alternans
Synonyms: *Trigonium alternans, Biddulphia alternans*
(LM, girdle view, image by C. Assadi)

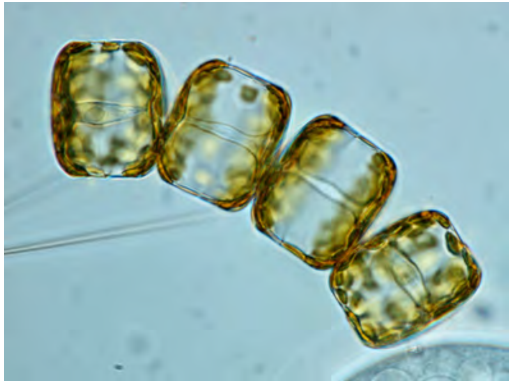
NOTE:
Click on the arrow icon to be taken back to the taxonomic tree.

Detonula sp.
(LM, girdle view)

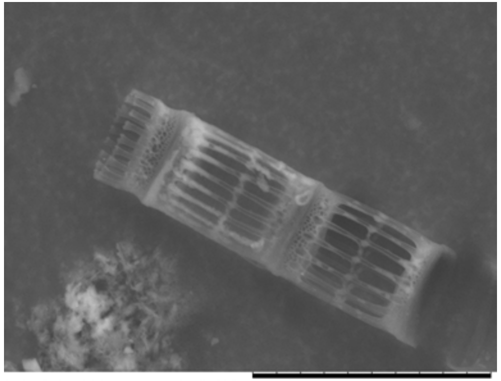
Detonula confervacea
Synonyms: *Lauderia confervacea*
(LM, girdle view, image by A-T. Skjevik)

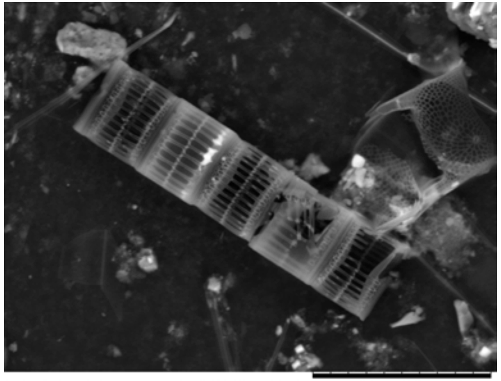


Lauderia sp.
(LM, girdle view)



Porosira sp.
(LM, girdle view)





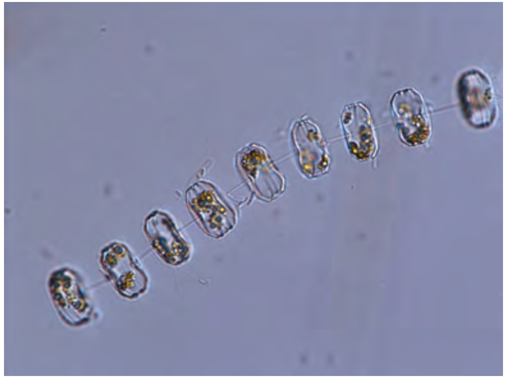
Skeletonema sp.
(SEM, girdle view, x4.0k, 20 μm scale)

Skeletonema sp.
(SEM, girdle view, x2.0k, 30 μm scale)

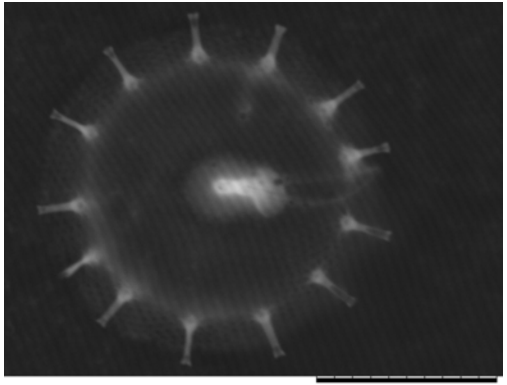
Skeletonema costatum
(LM, girdle view)

Skeletonema costatum
(LM, girdle view)

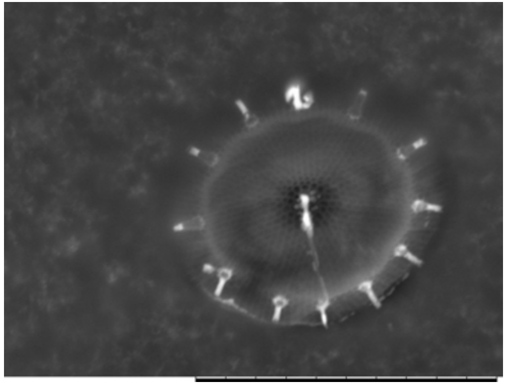
Skeletonema costatum
(LM, girdle view)



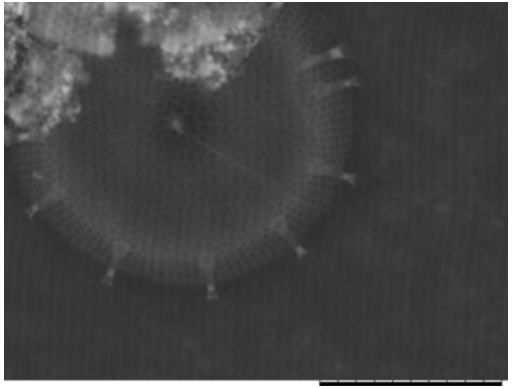
Thalassiosira nordenskioeldii
(LM, girdle view)



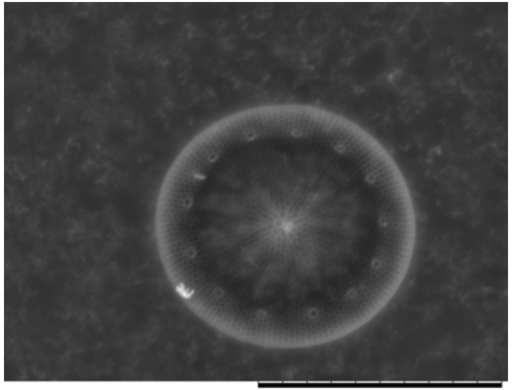
Thalassiosira nordenskioeldii
(SEM, outer valve view, x6.0k, 10 μm scale, image by author)



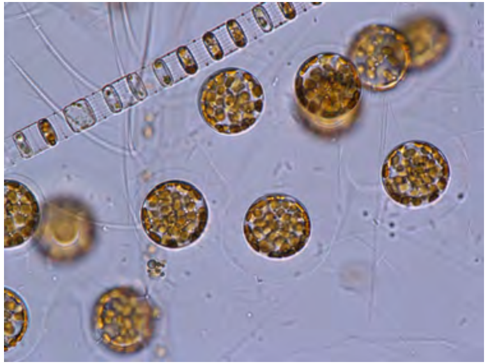
Thalassiosira nordenskioeldii
(SEM, outer valve view, x5.0k, 20 μm scale, image by author)



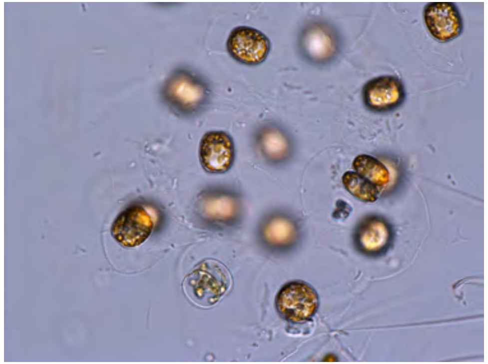
Thalassiosira nordenskioeldii
(SEM, outer valve view, x6.0k, 10 μm scale, image by author)



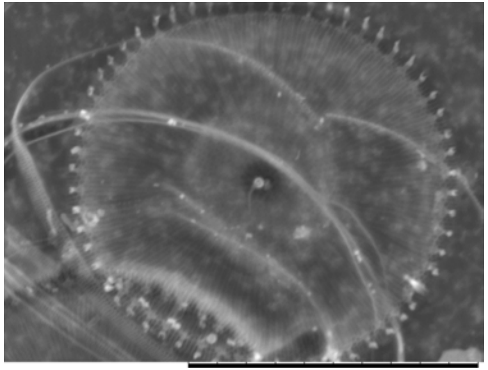
Thalassiosira nordenskioeldii
(SEM, inner valve view, x4.0k, 20 μm scale, image by author)



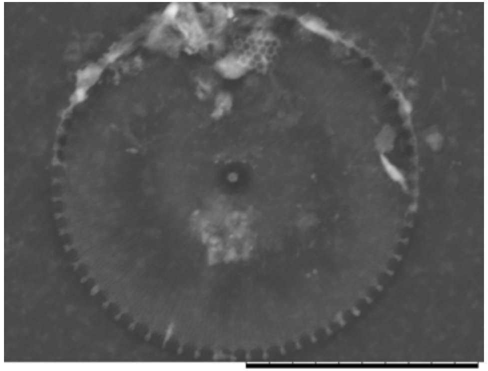
Thalassiosira subtilis
(LM, valve view)



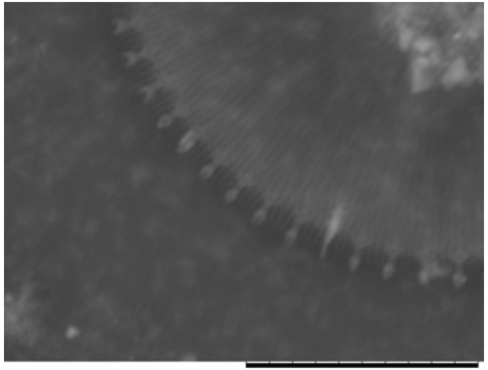
Thalassiosira subtilis
(LM, girdle view)



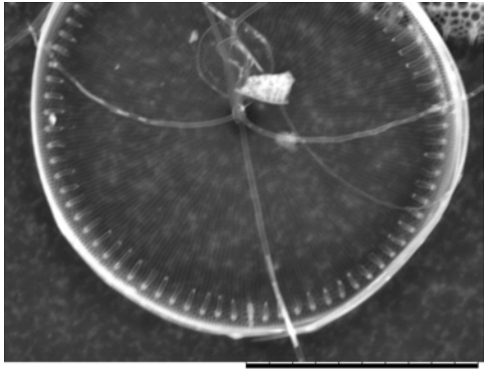
Thalassiosira rotula
Synonym: *Coscinodiscus rotulus*
(SEM, outer valve view, x5.0k, 20 μm scale)



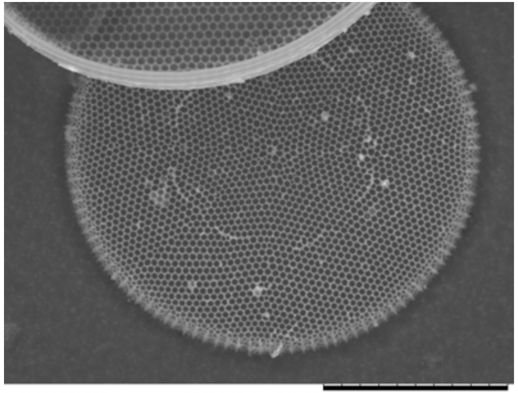
Thalassiosira rotula
Synonym: *Coscinodiscus rotulus*
(SEM, outer valve view,
X4.0k, 20 μm scale)



Thalassiosira rotula
Synonym: *Coscinodiscus rotulus*
(SEM, outer valve view,
x8.0k, 10 μm scale)



Thalassiosira rotula
Synonym: *Coscinodiscus rotulus*
(SEM, inner valve view,
x4.0k, 20 μm scale)



Thalassiosira anguste-lineate
Synonym: *Coscinodiscus angustelineatus*
(SEM, outer valve view,
x2.0k, 30 µm scale)

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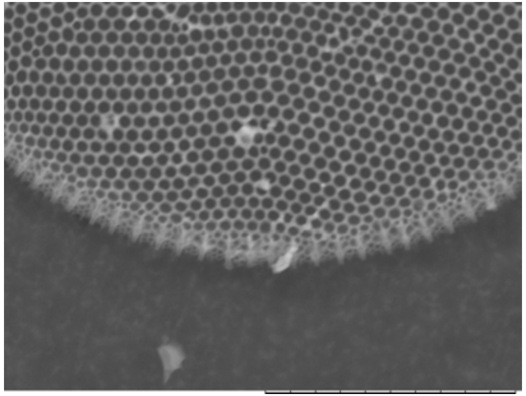
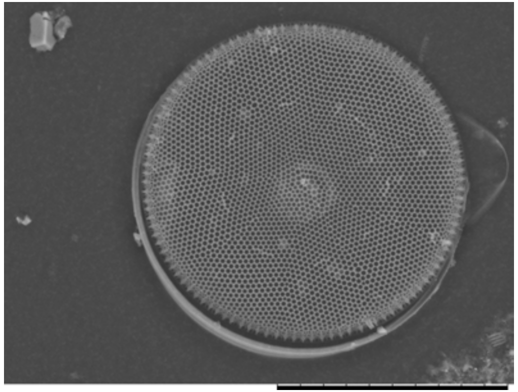
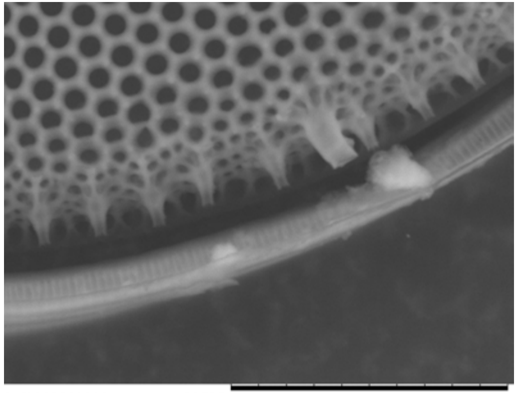


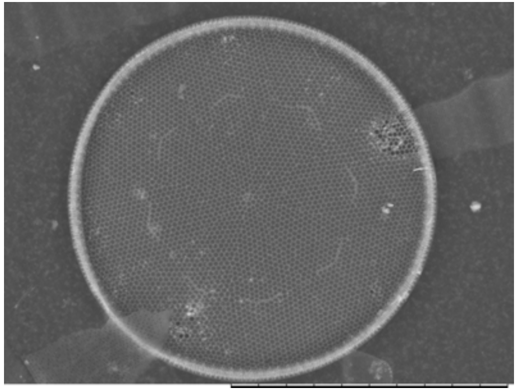
Thalassiosira anguste-lineate
Synonym: *Coscinodiscus angustelineatus*
(SEM, outer valve view,
x4.0k, 20 µm scale)



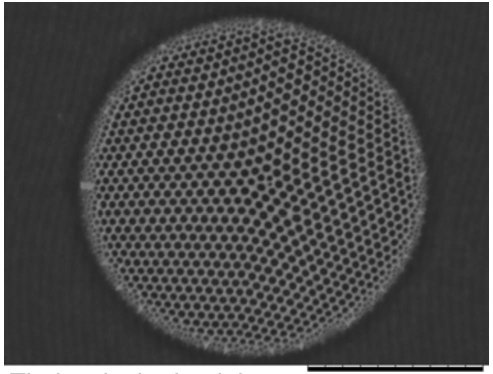
Thalassiosira anguste-lineate
Synonym: *Coscinodiscus angustelineatus*
(SEM, outer valve view,
x1.5k, 50 µm scale)



Thalassiosira anguste-lineate
Synonym: *Coscinodiscus angustelineatus*
(SEM, outer valve view,
x9.0k, 10 µm scale)



Thalassiosira anguste-lineate
Synonym: *Coscinodiscus angustelineatus* (SEM, inner valve view,
x1.8k, 50 µm scale)



Thalassiosira lentiginosa
Synonym: *Coscinodiscus lentiginosus*
(SEM, outer valve view,
x2.0k, 30 μm scale, image by author)

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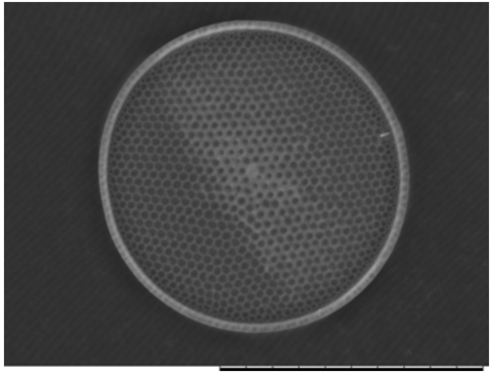
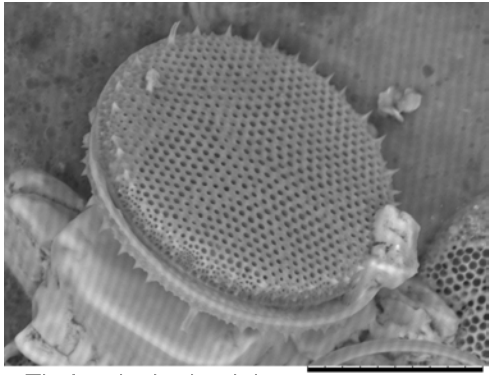
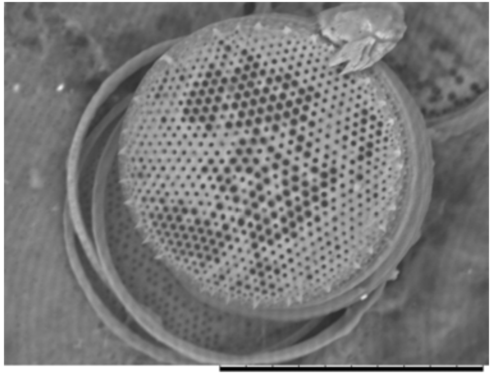
p.15



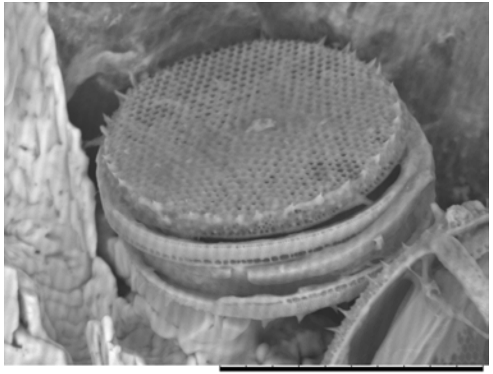
Thalassiosira lentiginosa
Synonym: *Coscinodiscus lentiginosus*
(SEM, inner valve view,
x1.8k, 50 μm scale, image by author)



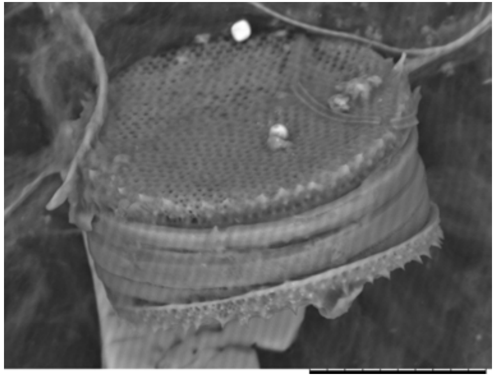
Thalassiosira lentiginosa
Synonym: *Coscinodiscus lentiginosus*
(SEM, x2.0k, 30 μm scale, image by author)



Thalassiosira lentiginosa
Synonym: *Coscinodiscus lentiginosus*
(SEM, x1.8k, 50 μm scale, image by author)



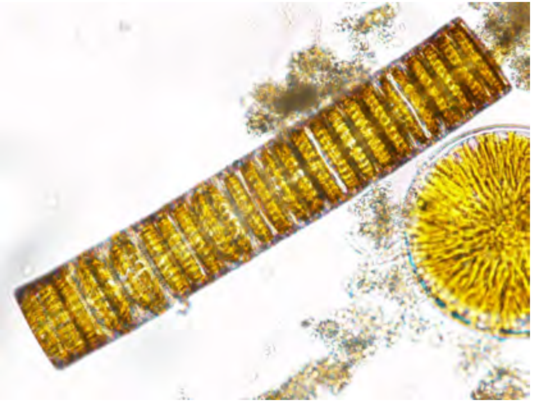
Thalassiosira lentiginosa
Synonym: *Coscinodiscus lentiginosus*
(SEM, girdle view,
x1.8k, 50 μm scale, image by author)



Thalassiosira lentiginosa
Synonym: *Coscinodiscus lentiginosus*
(SEM, girdle view,
x2.0k, 30 μm scale, image by author)

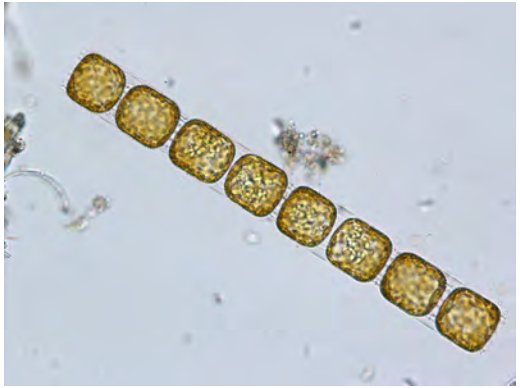
Paralia sulcata
(LM, girdle view,
image by G. Hannach)

Stephanopyxis turris
(LM, girdle view)



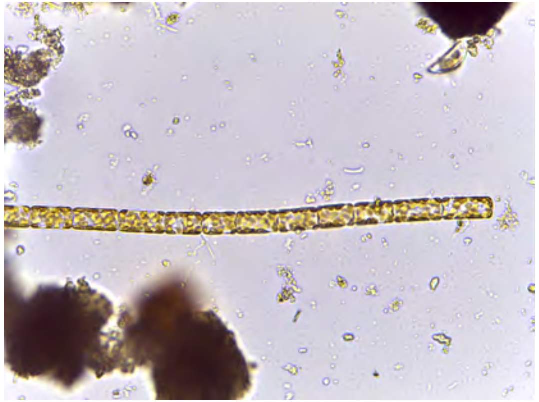
Melosira varians
(LM, girdle view)

Melosira moniliformis
(LM, girdle view,
image by M. Himemiya)



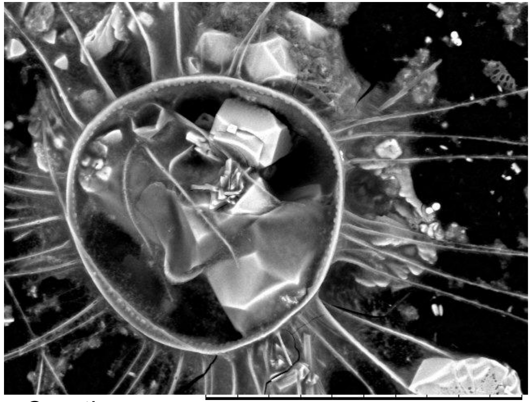
Melosira arctica
Synonym: *Gaillonella arctica*
(LM, girdle view)

Melosira arctica
Synonym: *Gaillonella arctica*
(LM, girdle view)

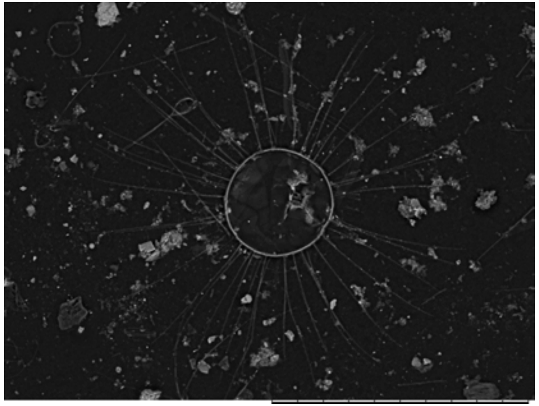


Leptocylindrus danicus
(LM, girdle view)

Corethron sp. dividing
(LM, girdle view)

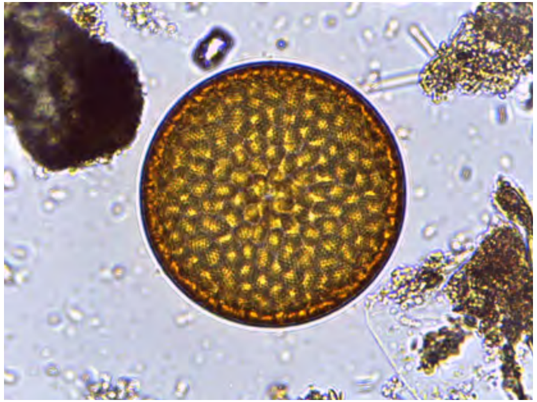


Corethron sp.
(SEM, inner valve view,
x1.0k, 100 µm scale)

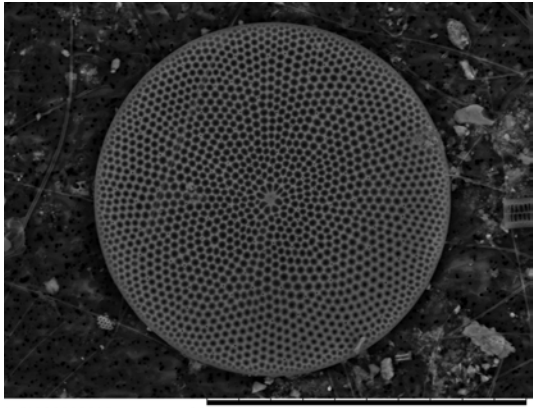


Corethron sp.
(SEM, inner valve view,
x400, 200 µm scale)

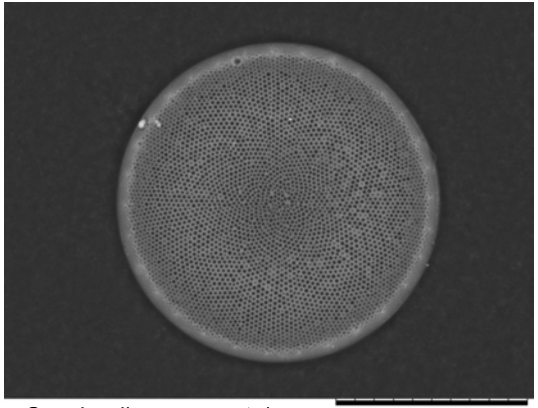
Corethron pennatum
(LM, girdle view)



Coscinodiscus sp.
(LM, valve view)



Coscinodiscus sp.
(SEM, outer valve view,
x1.0k, 100 µm scale)



Coscinodiscus curvatulus
Synonym: *Actinocyclus curvatulus*
(SEM, outer valve view, x1.2k, 50 µm scale,
image by author)

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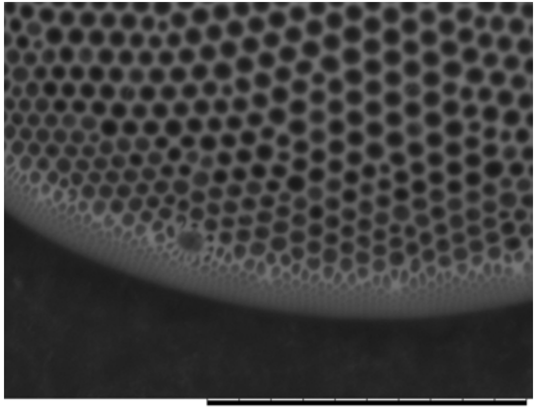
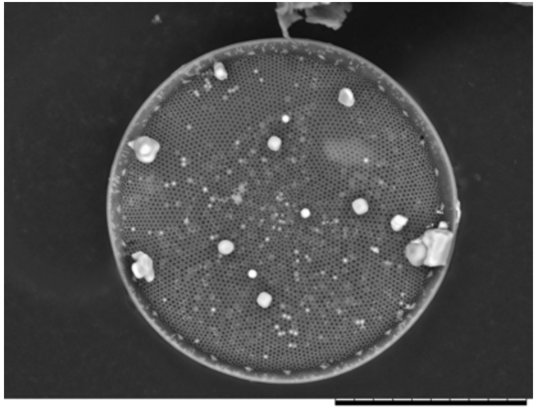
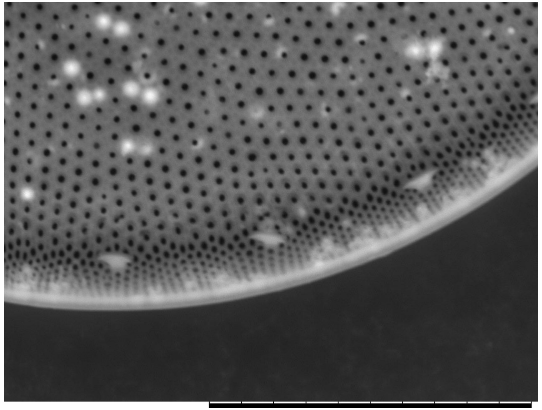


Coscinodiscus curvatulus
Synonym: *Actinocyclus curvatulus*
(SEM, outer valve view, x5.0k, 20 µm scale,
image by author)



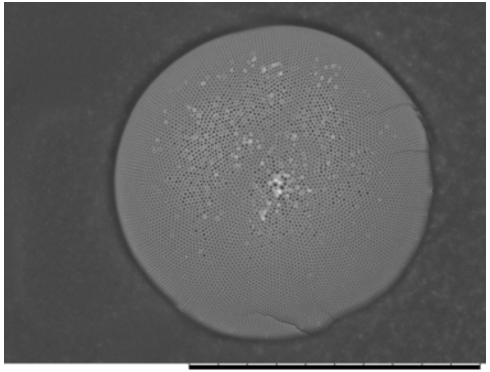
Coscinodiscus curvatulus
Synonym: *Actinocyclus curvatulus*
(SEM, inner valve view, x1.2k, 50 µm scale,
image by author)



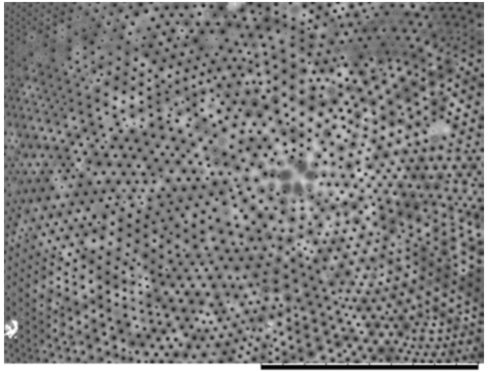
Coscinodiscus curvatulus
Synonym: *Actinocyclus curvatulus*
(SEM, inner valve view, x5.0k, 20 µm scale,
image by author)

Thalassiosira oculus-iridis
Synonym: *Coscinodiscus oculus-iridis*
(LM, valve view)

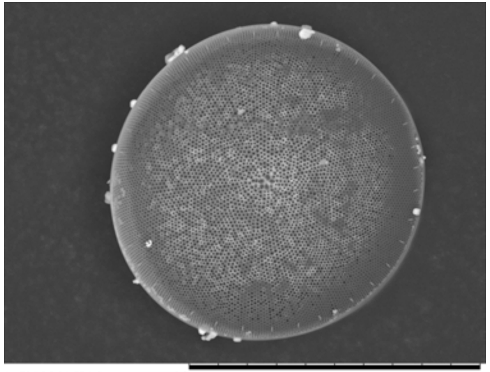
Thalassiosira oculus-iridis
Synonym: *Coscinodiscus oculus-iridis*
(LM, valve view)



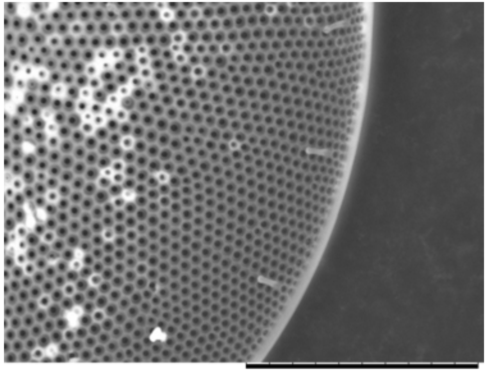
Thalassiosira oculus-iridis
Synonym: *Coscinodiscus oculus-iridis*
(SEM, outer valve view, x1.0k, 100 μm scale, image by author)



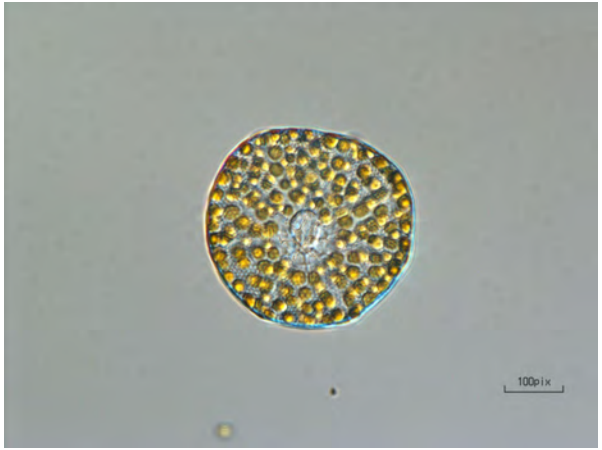
Thalassiosira oculus-iridis
Synonym: *Coscinodiscus oculus-iridis*
(SEM, outer valve view, x2.5k, 30 μm scale, image by author)



Thalassiosira oculus-iridis
Synonym: *Coscinodiscus oculus-iridis*
(SEM, inner valve view, x1.0k, 100 μm scale, image by author)



Thalassiosira oculus-iridis
Synonym: *Coscinodiscus oculus-iridis*
(SEM, inner valve view,
x4.0k, 20 μm scale, image by author)



Asteromphalus sp.
(LM, valve view)

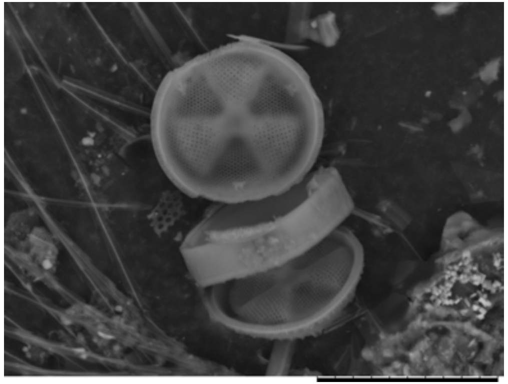
↩

Asteromphalus sp.
(LM, valve view)

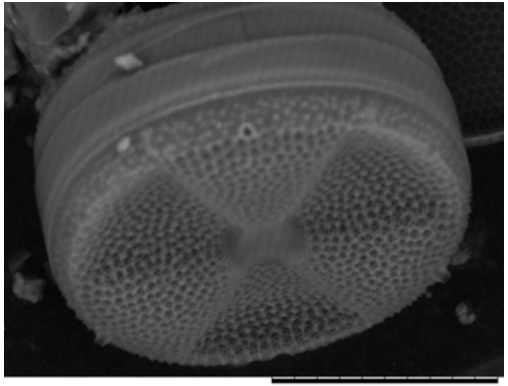
Asteromphalus hookeri
Synonym: *Asteromphalus humboldtii*
(LM, valve view)

↩

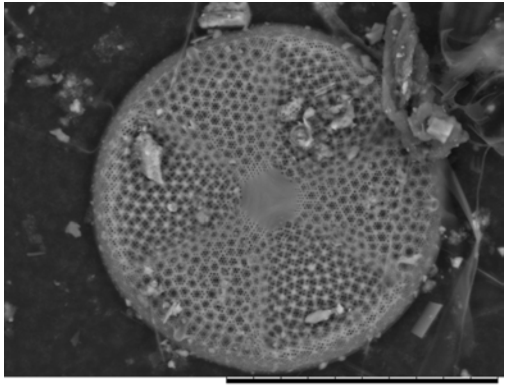
Arachnoidiscus ornatus
(LM, valve view)



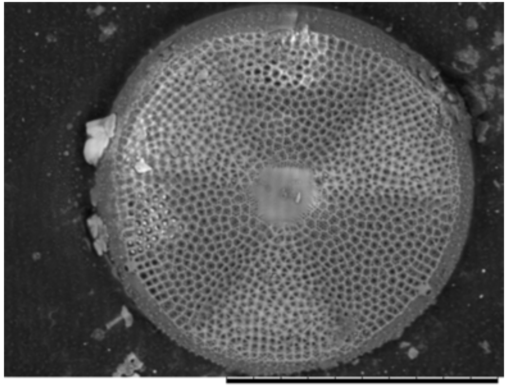
Actinoptychus senarius
Synonym: *Actinoptychus undulatus*
(SEM, x2.0k, 30 μm scale)



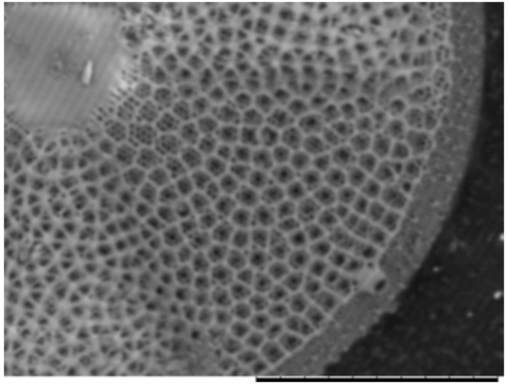
Actinoptychus senarius
Synonym: *Actinoptychus undulatus*
(SEM, x2.5k, 30 μm scale)



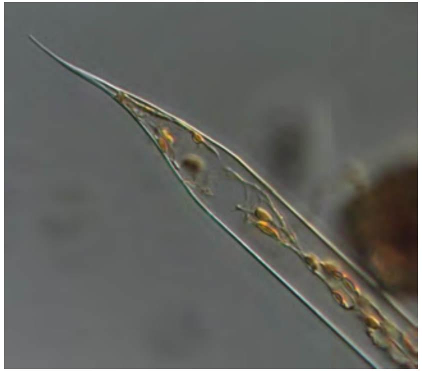
Actinoptychus senarius
Synonym: *Actinoptychus undulatus*
(SEM, outer valve view, x1.8k, 50 μm scale)



Actinoptychus senarius
Synonym: *Actinoptychus undulatus*
(SEM, outer valve view, x1.8k, 50 μm scale, image by author)



Actinoptychus senarius
Synonym: *Actinoptychus undulatus*
(SEM, outer valve view, x4.0k, 20 μm scale, image by author)



Pseudosolenia calcar-avis
Synonym: *Rhizosolenia calcar-av*
(LM, girdle view,
image by A-T. Skjevik)

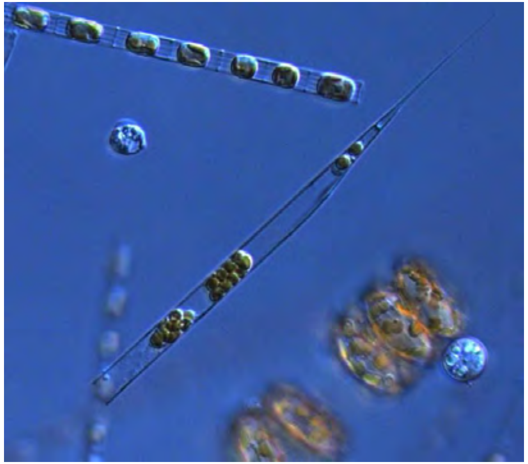
Rhizosolenia sp.
Synonym: *Proboscia* sp.
(LM, girdle view)

Rhizosolenia sp.
Synonym: *Proboscia* sp.
(LM, girdle view)

Rhizosolenia sp.
Synonym: *Proboscia* sp.
(SEM, girdle view, x1.8k, 50 μm scale)

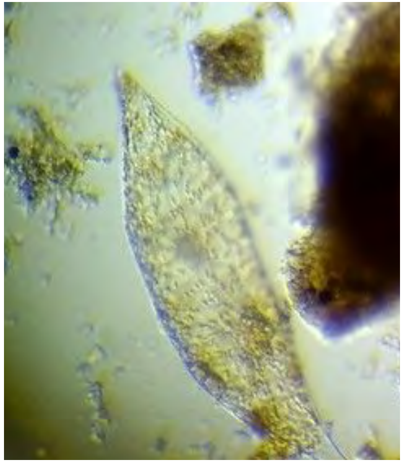
Rhizosolenia setigera
(LM, girdle view,
image by S. Martinez)

Rhizosolenia styliformis
(LM, girdle view,
image by N. Penrose)



Rhizosolenia hebetata f. semispina
(LM, girdle view,
image by A-T. Skjevik)

Rhizosolenia robusta
(LM, girdle view, image by P. Priester)



Rhizosolenia robusta
(LM, girdle view,
image by P. Priester)

Eucampia sp.
(LM, girdle view)

Eucampia zodiacus
(LM, girdle view)

Eucampia striata
Synonym: *Guinardia striata, Rhizosolenia stolterfothii*
(LM, girdle view)

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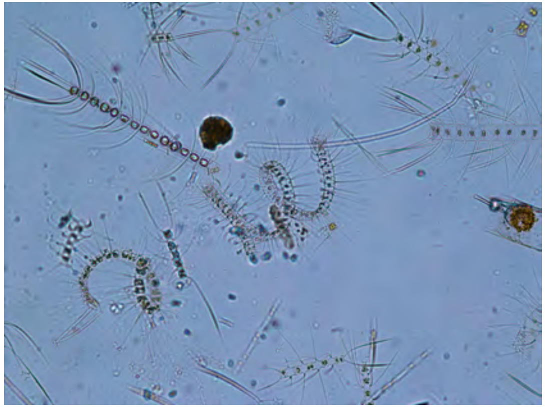
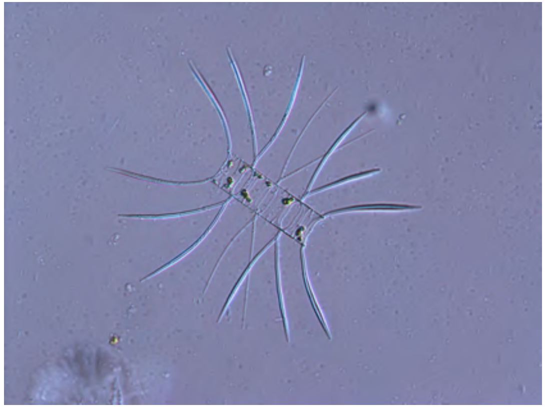


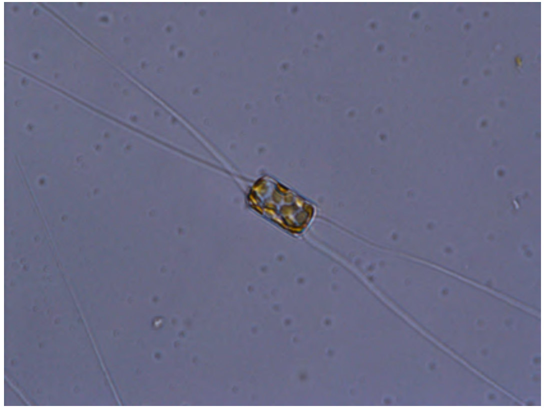
Chaetoceros spp.
(LM)

Chaetoceros spp.
(LM, girdle view)

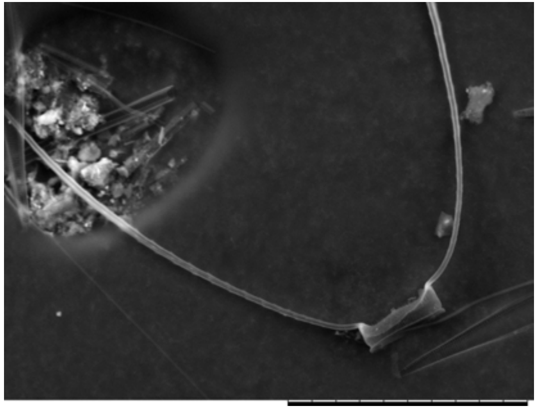


Chaetoceros sp.
(LM, girdle view)

Chaetoceros sp.
(LM, girdle view)

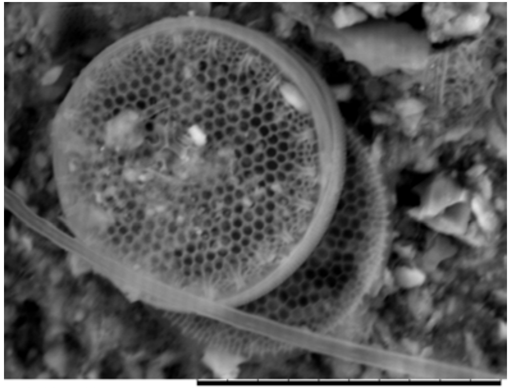


Chaetoceros sp.
(LM, girdle view)

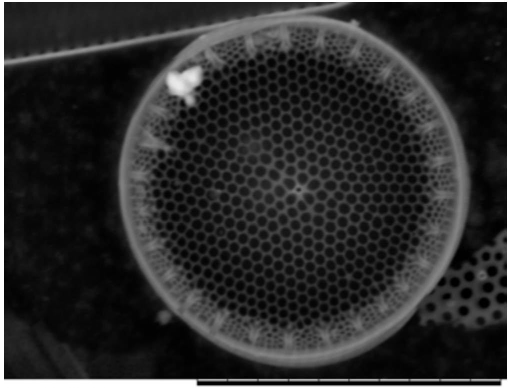


Chaetoceros sp.
(SEM, girdle view, x1.5k, 50 µm scale)

Chaetoceros decipiens
(LM, girdle view)



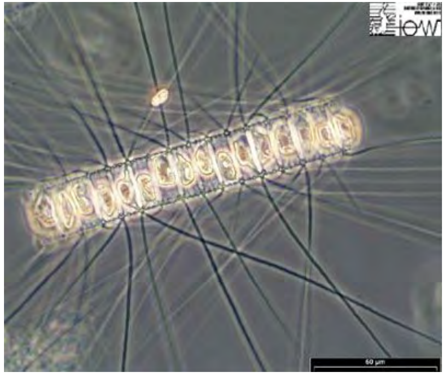
Chaetoceros decipiens
(SEM, valve view, x5.0k, 20 μm scale)



Chaetoceros decipiens
(SEM, inner valve view, x5.0k, 20 μm scale)

Chaetoceros didymus
(LM, girdle view)

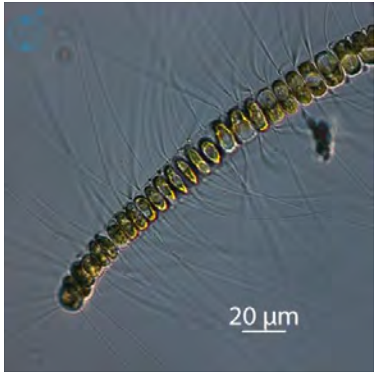
Chaetoceros didymus
(LM, girdle view)



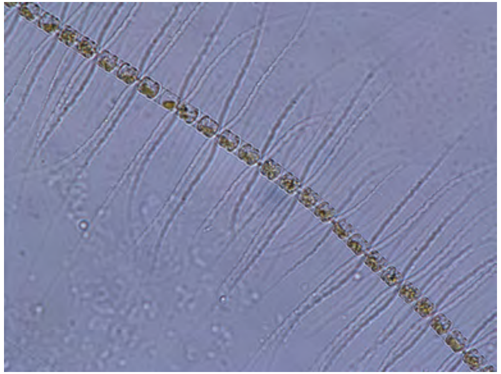
Chaetoceros constrictus
(LM, girdle view, image by R. Hansen and S. Busch)

Chaetoceros curvisetus
(LM, image by S. Anderson)

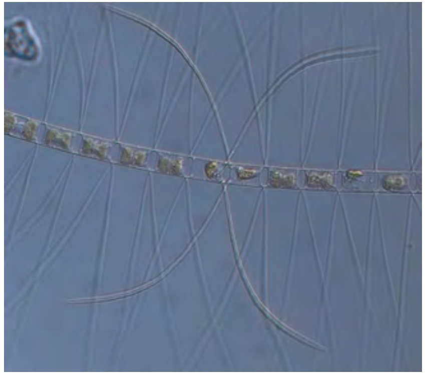
Chaetoceros debilis
(LM, girdle view)



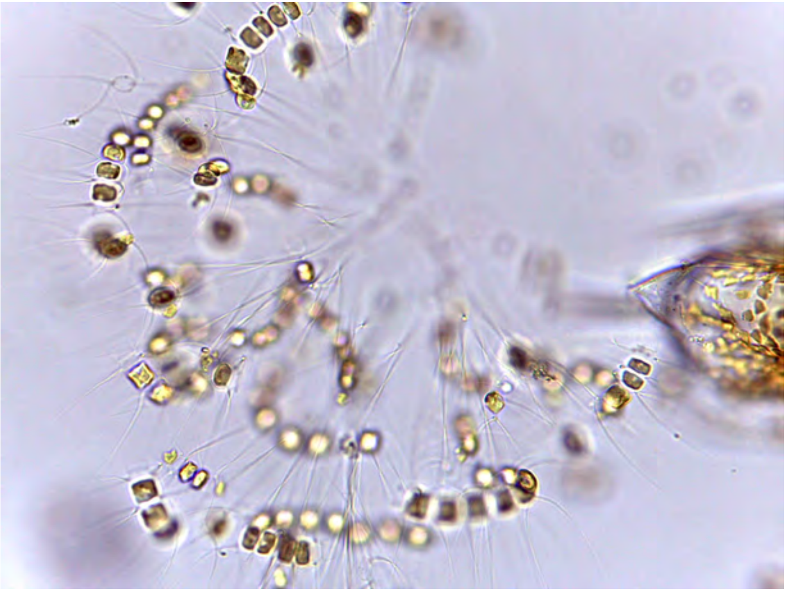
Chaetoceros tortissimus
(LM, girdle view, image by alexandra)



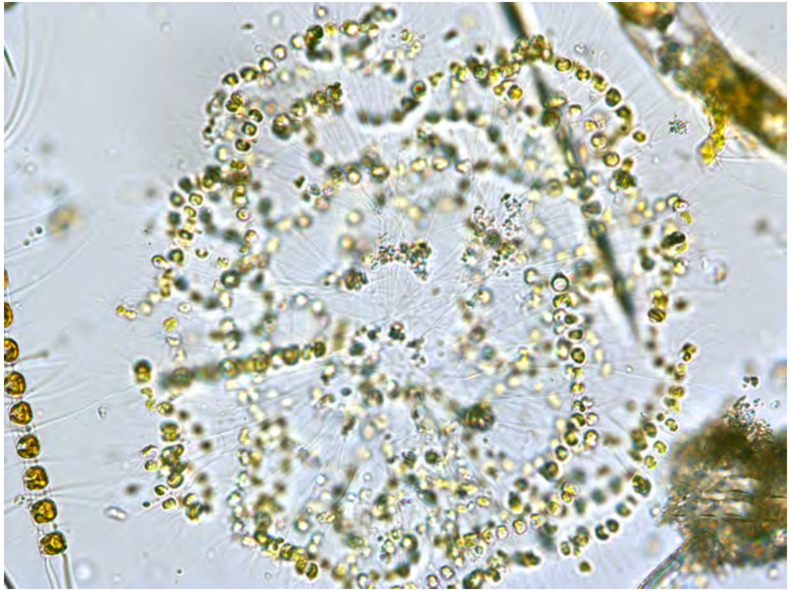
Chaetoceros radicans
(LM, girdle view)



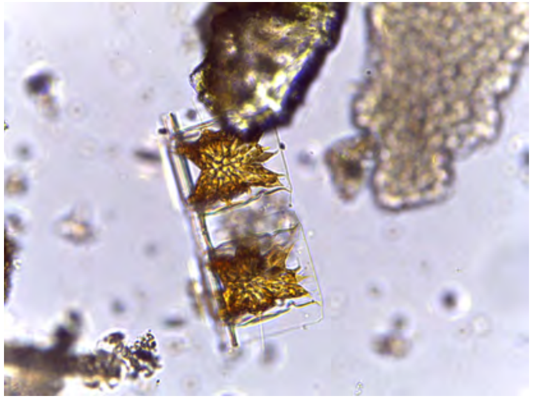
Chaetoceros affinis
(LM, girdle view, image by A-T Skjevik)



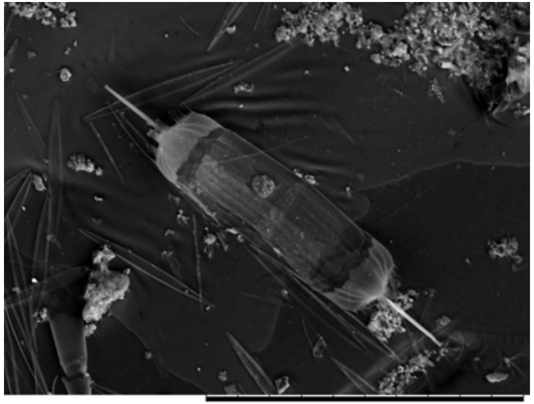
Chaetoceros socialis
(LM)



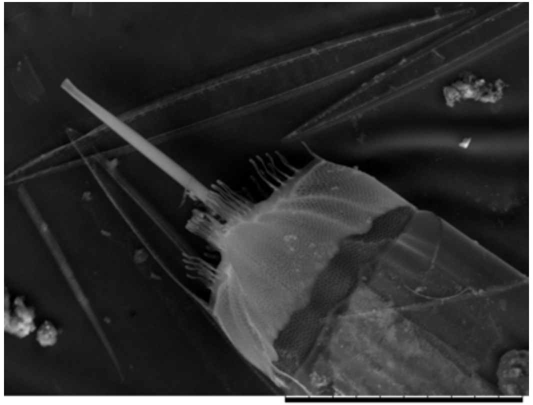
Chaetoceros socialis
(LM)



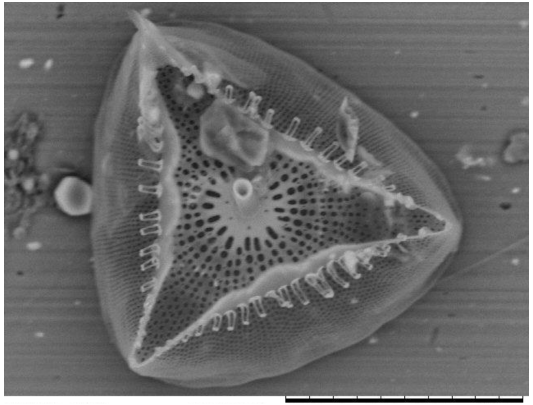
Lithodesmium undulatum
(LM, girdle view)



Ditylum sp.
(SEM, girdle view,
x500, 200 µm scale)



Ditylum sp.
(SEM, girdle view,
x1.5, 50 µm scale)



Ditylum sp.
(SEM, valve view,
x2.5, 30 µm scale)

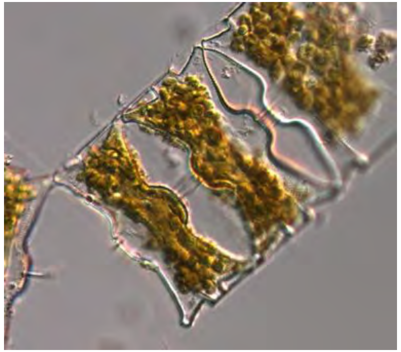
Ditylum brightwellii
Synonym: *Triceratium brightwellii*
(LM, girdle view)

Ditylum brightwellii
Synonym: *Triceratium brightwellii* (LM, girdle view)

Heliotheca sp.
(LM)

Heliotheca sp.
(LM)

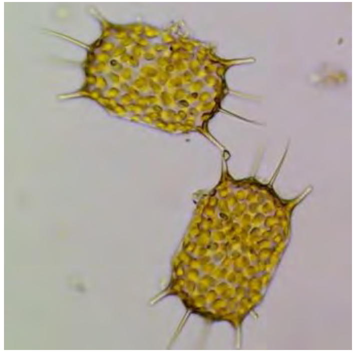
Heliotheca tamesis
Synonym: *Streptotheca thamensis*
(LM)



Odontella aurita
Synonym: *Biddulphia aurita*
(LM, girdle view,
image by A-T. Skjevik)

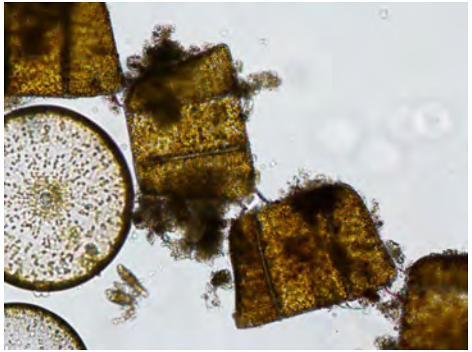
Odontella obtusa
Synonym: *Biddulphia aurita var. obtusa*
(LM, girdle view, image by G. Drebes)

Odontella longicruris
Synonym: *Hobaniella longicruris, Biddulphia longicruris*
(LM, girdle view)



Trieres mobiliensis
Synonym: *Odontella weissflogii, Biddulphia mobiliensis*
(LM, girdle view, image by GTMResearchReserve)

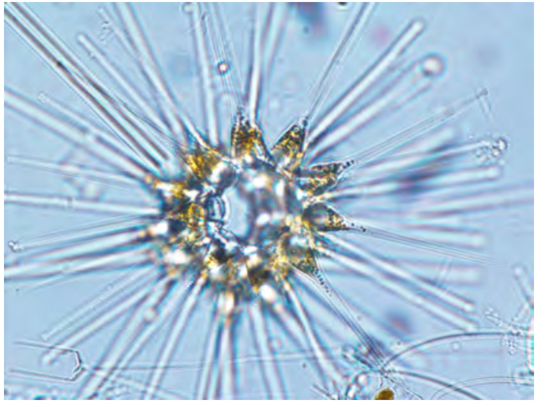
Isthmia nervosa
(LM, girdle view)



Isthmia nervosa
(LM, girdle view)

Asterionella japonica
Synonym: *Asterionellopsis glacialis*
(LM)

Asterionella japonica
Synonym: *Asterionellopsis glacialis*
(LM)



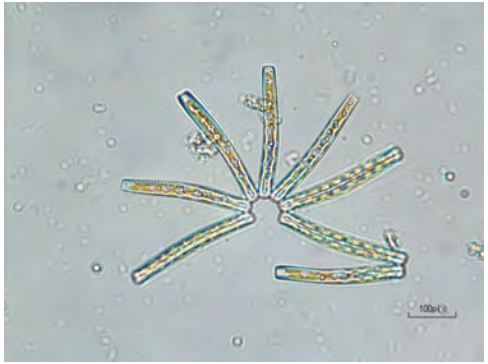
Asterionella japonica
Synonym: *Asterionellopsis glacialis*
(LM)

Asterionella formosa
(LM, image by J. Parmentier)

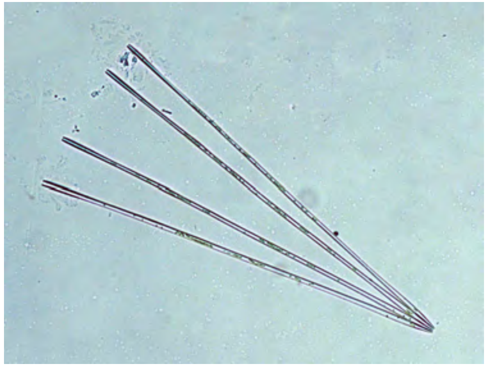
Thalassiothrix sp.
(LM)

Thalassionema nitzschioides
Synonym: *Synedra nitzschioides, Thalassiothrix nitzschioides*
(LM)

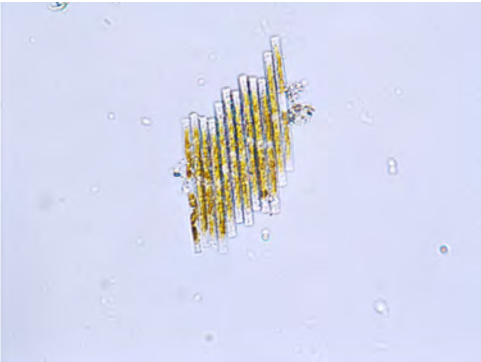
Thalassionema nitzschioides
Synonym: *Synedra nitzschioides, Thalassiothrix nitzschioides*
(LM)



Thalassionema nitzschioides
Synonym: *Synedra nitzschioides, Thalassiothrix nitzschioides*
(LM)

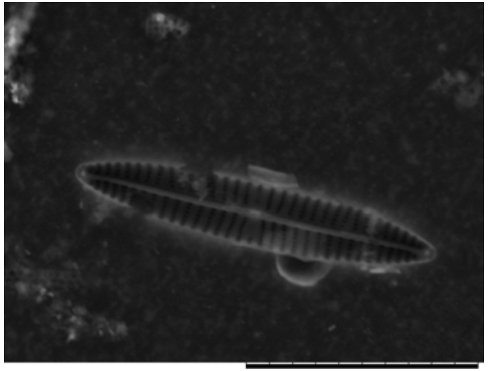


Lioloma pacificum
Synonym: *Thalassiothrix mediterranea var. pacifica*
(LM)

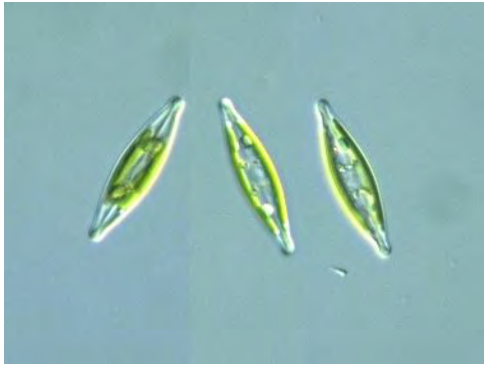


Bacillaria paxillifer
Synonym: *Bacillaria paradoxa, Vibrio paxillifer, Nitzschia paradoxa*
(LM)

Achnanthes sp.
(LM, girdle view)



Navicula sp.
(SEM, valve view,
x4.0k, 20 μm scale)



Navicula sp.
(LM, valve view,
image by Y. Tuskii)

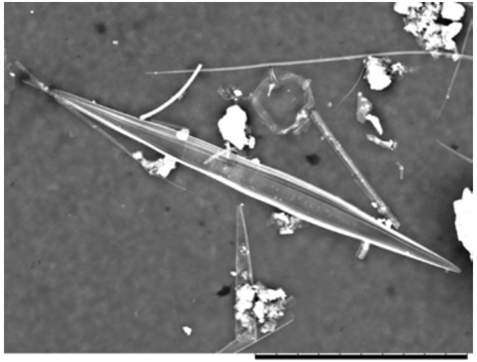
Amphiprora sp.
(LM, valve view,
image by Y. Tsukii)

Tropidoneis sp.
(LM, valve view)

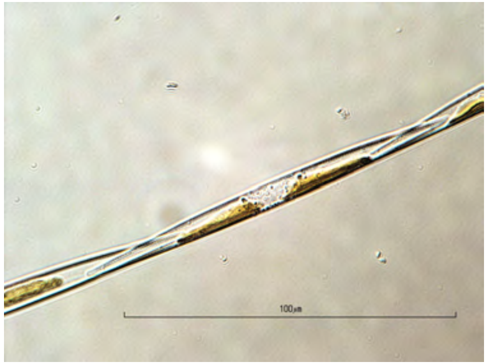
Tropidoneis antarctica
Synonym: *Navicula challengeri, Membraneis challengeri*
(LM, valve view)

Pleurosigma sp.
(LM, valve view)

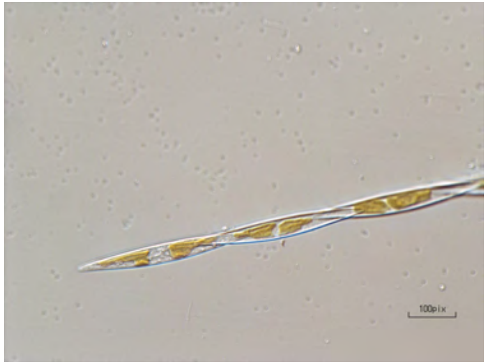
Gyrosigma balticum
Synonym: *Pleurosigma balticum*
(LM, valve view, image by Proyecto Agua)



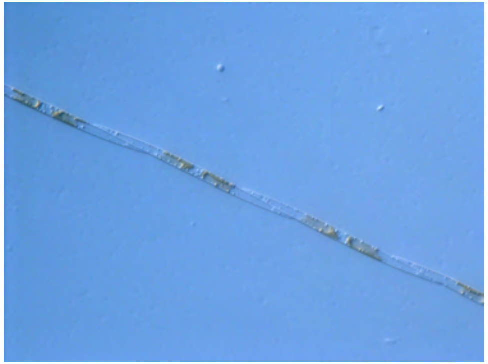
Pseudo-nitzschia sp.
(SEM, valve view, x1.5k, 50 µm scale)



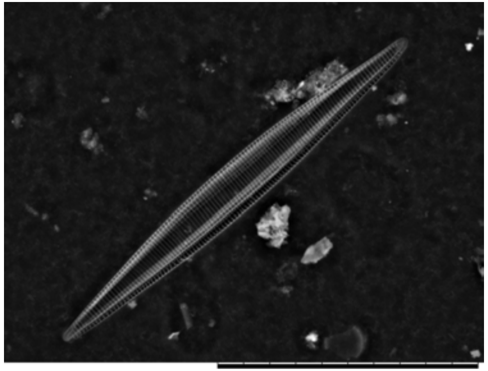
Pseudo-nitzschia sp.
(LM, valve view)



Pseudo-nitzschia sp.
(LM, valve view)



Pseudo-nitzschia sp.
(LM, valve view)

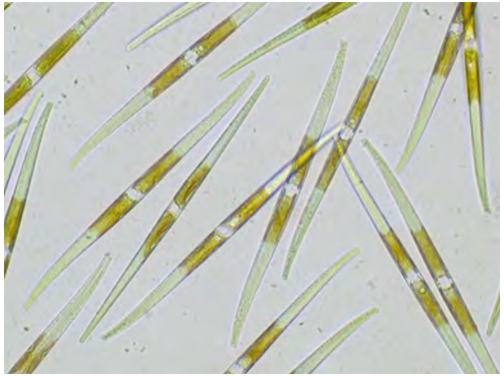


Nitzschia sp.
(SEM, valve view,
x1.8k, 50 µm scale)

Nitzschia sp.
(LM, girdle view,
image by K. Peters)

Nitzschia closterium
Synonym: *Cylindrotheca closterium, Phaeodactylum tricornutum*
(LM, valve view, image by A. Grogan)

Nitzschia longissima
Synonym: *Nitzschiella longissima*
(SEM, valve view,
image by S. Martinez)



Nitzschia sigma
Synonym: *Sigmatella sigma*
(LM, valve view,
image by Z. Mustafaeva and
V. A. Chepurnov)

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Odontella obtusa LM image by G. Drebes: https://planktonnet.awi.de/sci_images_detail.php?itemid=12711

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Amphiprora sp. LM image by Y. Tsukii: http://protist.i.hosei.ac.jp/PDB/Images/Heterokontophyta/Raphidineae/Entomoneis/sp_01.html

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Nitzschia longissima LM image by Sarka Martinez: https://www.inaturalist.org/photos/2614230

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https://bccm.belspo.be/catalogues/dcg-species-details?SPECIES_NAME=Nitzschia+sigma+%28K%C3%BCtzing%29+W.+Smith

Appendix C:

“A Basic Key to Common Phytoplankton in San Francisco Bay” contains (1) morphological dichotomous decision trees that include common dinoflagellates and the most significant or well-represented diatom genera and species, based on Keith (2018), found in San Francisco Bay and (2) a taxonomic species list. This basic key is intended for an audience with little to no knowledge of phytoplankton terminology and research, and it is ideal as a supplemental educational tool for school-aged children.

A Basic Key to
Common Phytoplankton in San Francisco Bay

SF PHYTOPLANKTON KEYS

UNIVERSITY OF SAN FRANCISCO,
DEPARTMENT OF BIOLOGY

Table of Contents

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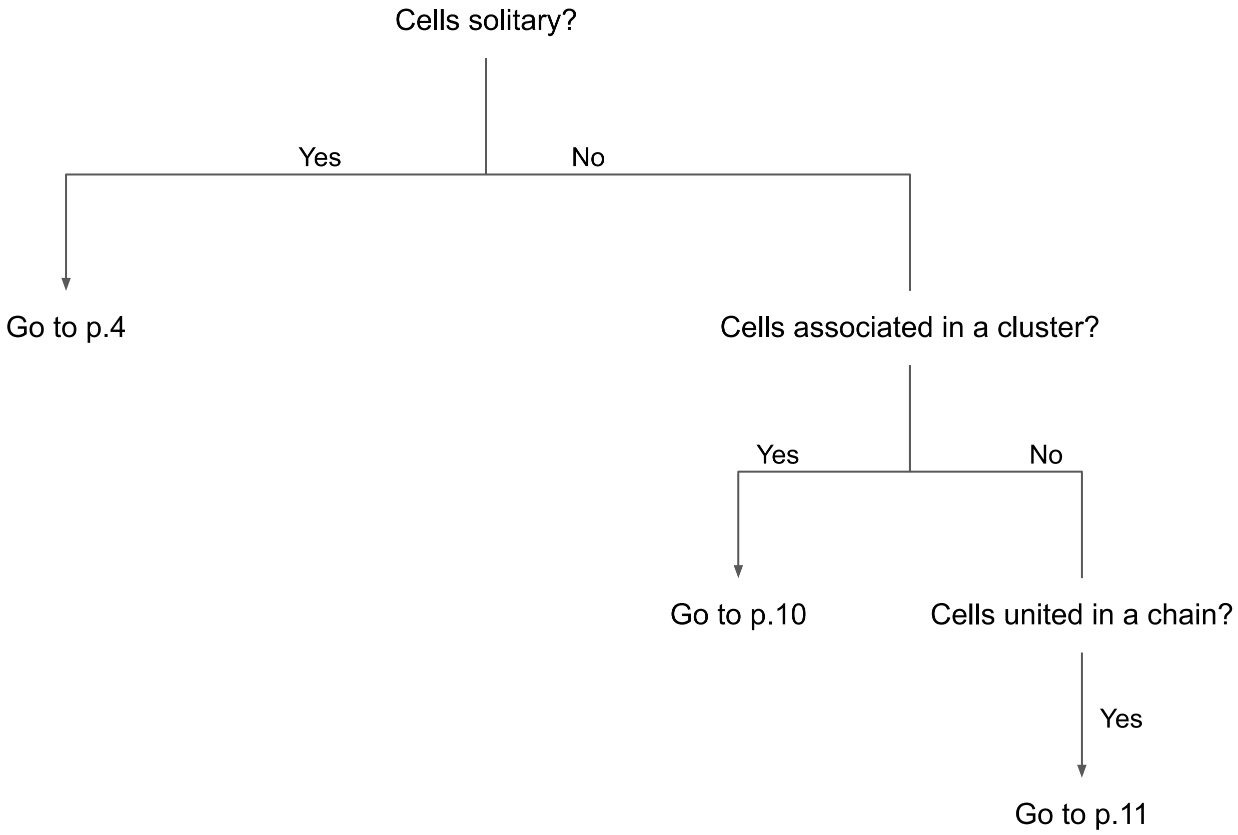


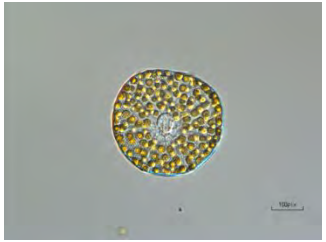
Highlight Key

Green - Centric Diatoms
Purple - Pennate Diatoms
Orange - Dinoflagellates

Cells are solitary

Cell is "rust" colored?

- Yes → Go to p.7
- No → Cell outline is circular?
  - Yes → Cell has a star-like shape at the center?
    - Yes → *Asteromphalus*



    - No → *Coscinodiscus oculus iridis*

  - No → Cell outline is triangular?
    - Yes → *Triceratium* sp.

    - No → Cell outline looks like a bowtie or hourglass?
      - Yes → *Amphiprora* sp.

(image by Y. Tsukii)

      - No → Go to p.5

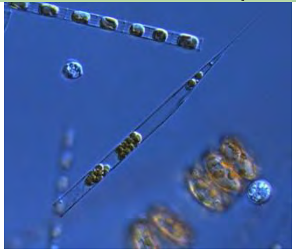
Cell outline is tube-shaped or pill-shaped?

- Yes → Has spines?
  - Yes → Has one spine on either end, looks like the cell is skewered?
    - Yes → *Ditylum brightwellii*

    - No → Has spines surrounding both rounded ends?
      - Yes → *Corethron pennatum*

  - No → *Navicula challengeri*

- No → Cell outline is rod-shaped?
  - Yes → Both ends of cell are sharp like a needle?
    - Yes → *Rhizosolenia semispina*



(image by A-T. Skjevik)

    - No → *Nitzschia* sp.

(image by K. Peters)

  - No → Go to p.6

Cell outline is canoe-shaped?

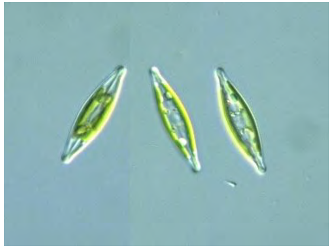
Yes

Cell is curved into a slight S-shape?

Yes → *Pleurosigma* sp.

No → Both tips/ends of the cell are rounded (not pointed)?

Yes → *Navicula* sp.



(image by Y. Tsukii)

No → Both tips/ends of the cell are extended into a long, needle-like shape?

Yes

Cell has two distinct yellow-green masses (chloroplasts) inside?

Yes → *Nitzschia closterium*

(image by A. Grogan)

No → *Nitzschia longissima*

(image by S. Martinez)

Cell outline is crescent moon-shaped?

Yes

Pyrocystis lunula

No

Cell has spikes or horns?

Yes

Cell has 3 prominent spikes or horns?

Yes

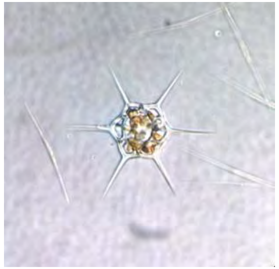
Go to p.8

No

Cell has more than 3 spikes or horns?

Yes

Dictyocha sp.

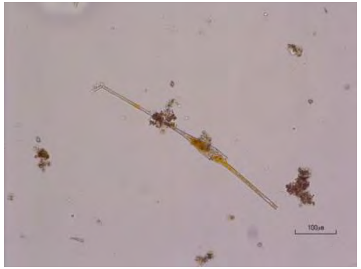


No

Cell has less than three prominent spikes or horns?

Yes

Tripos fusus



No

Go to p.9

Two horns are curved?

- Yes: Straight horn is off-center?
  - Yes: *Tripos gibberus*

    (image by Shimoda Plankton Team)
  - No: Straight horn is centered?
    - Yes: *Tripos muelleri*

      
- No: All horns are straight and cell is pentagon-shaped?
  - Yes: Pentagon-shaped cell is wide?
    - Yes: *Tripos furca*

      
    - No: Pentagon-shaped cell is narrow?
      - Yes: *Tripos lineatus*

        
  - No: Cell is greenish-brown (chloroplasts present)?
    - Yes: *Peridinium* sp.

      (image from PhycoKey)
    - No: *Protoperidinium* sp.

Cell outline is lilypad-shaped?

Yes — *Noctiluca scintillans*

No — Cell outline is teardrop-shaped?

Yes — *Prorocentrum* sp.

(image from PhycoKey)

No — Cell looks segmented like a pill bug?

Yes — *Polykrikos kofoidii*

(image by K. Bruun)

No — Cell looks like it has a fin?

Yes — *Dinophysis* sp.

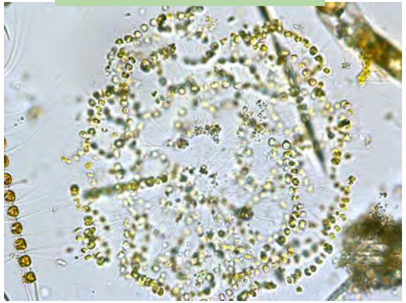
No — *Gymnodinium* sp.

Cells associated in a cluster

Cells united in chains within the cluster?

Yes

Chaetoceros socialis

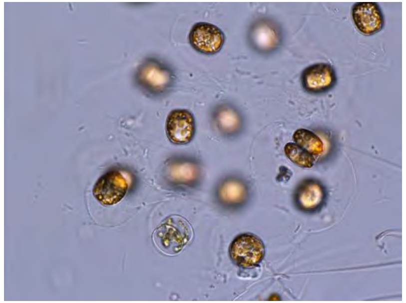


No

Cell outline is circular or disk-shaped?

Yes

Thalassiosira subtilis

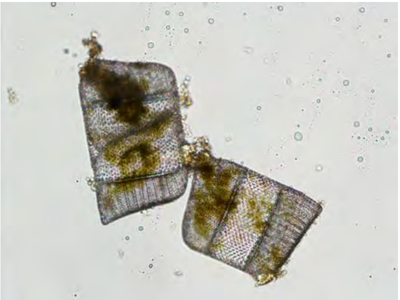


No

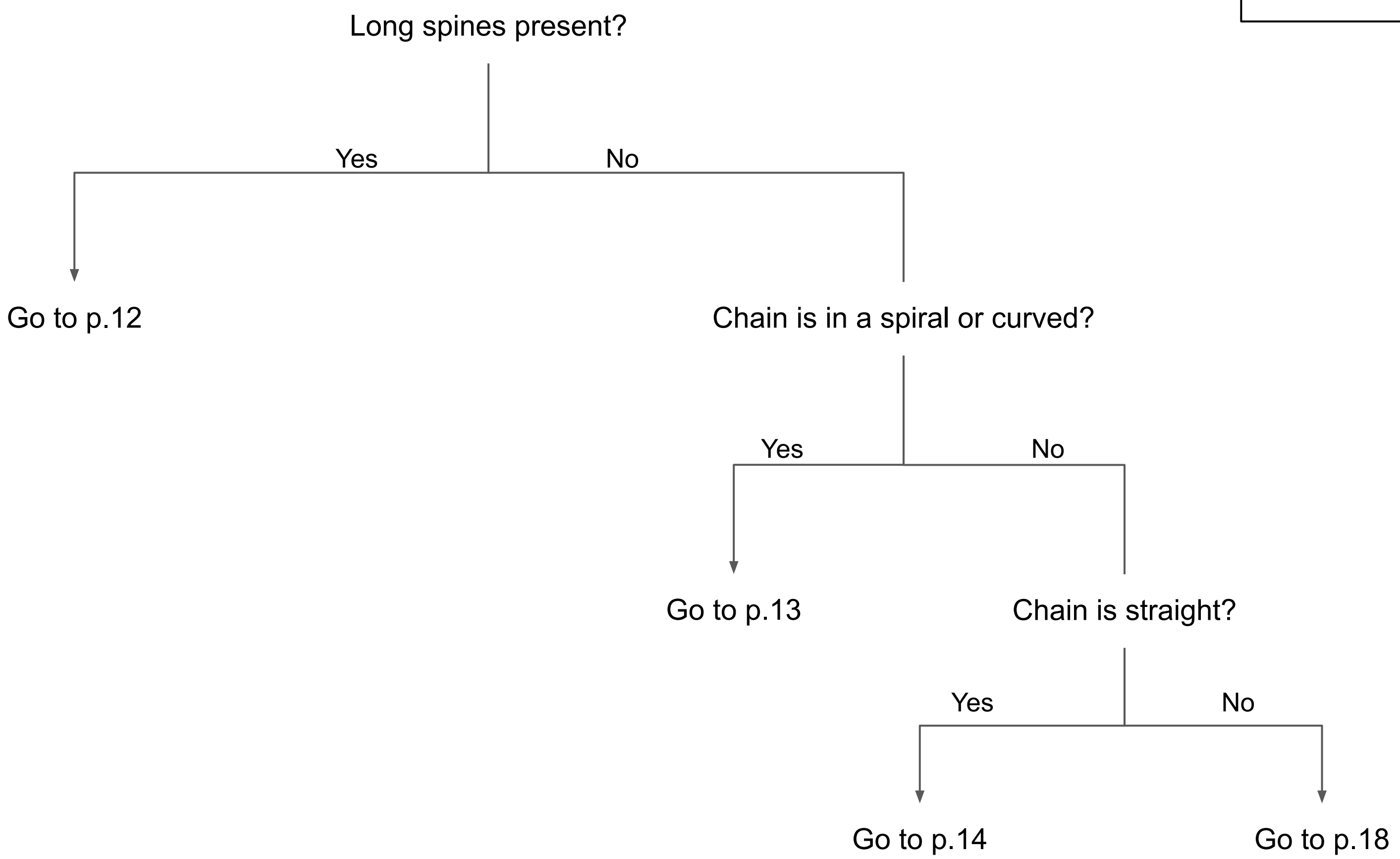
Cell outline looks like a trapezoid or rhombus?

Yes

Isthmia nervosa



Cells united in a chain



Chain is in a spiral or curved?

Yes → Cells connected by elevated corners?

- Yes → *Chaetoceros curvisetus*

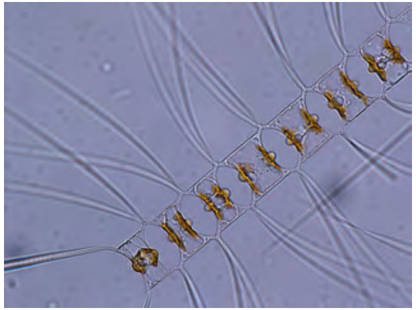
(image by S. Anderson)

- No → *Chaetoceros debilis*

No → Chain is straight?

Yes → Cells have a round bump at the center?

- Yes → *Chaetoceros didymus*



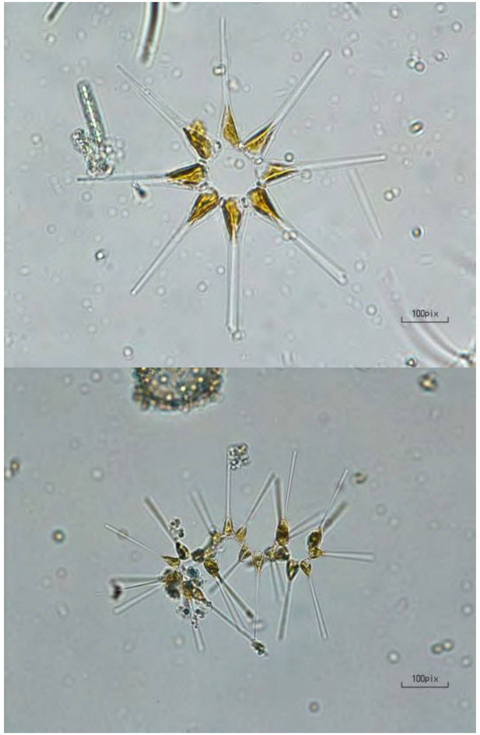
- No → *Chaetoceros decipiens*

Cells are bulb-shaped extending into spokes that point outwards?

Yes

No

Asterionella japonica



Cells are tube-shaped and connected at the corners, creating circular spaces between cells?

Yes

No

Cells are tube-shaped and no space between cells?

Yes

Eucampia zodiacus

Eucampia striata

Cell outline is tube-shaped or pill-shaped?

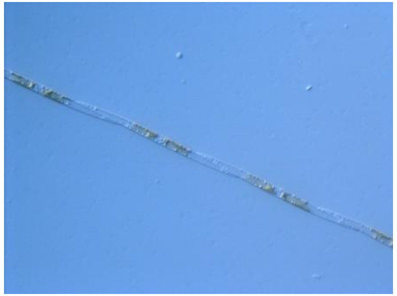
Yes | No

Go to p.15

Cells are shaped like toothpicks (long rods with pointed ends)?

Yes | No

Pseudo-nitzschia sp.



(image by GTMResearchReserve)

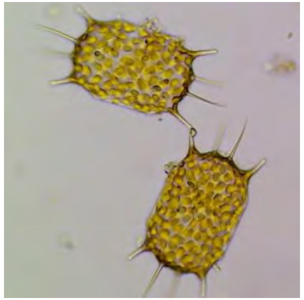
Cells connected at the corners by spikes?

Yes | No

Cell outline is dodecagonal (12 sides)?

Yes | No

Trieres mobiliensis

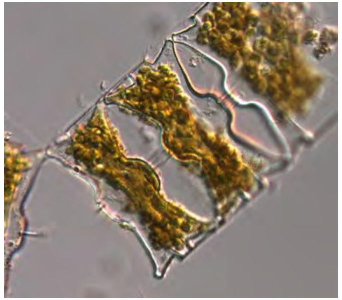


Hobaniella longicruris

Cells connected at the corners by triangular horns?

Yes

Odontella aurita



(image by A-T. Skjevik)

Cells linked together as pairs within the chain?

Yes → Cells linked together with numerous visible spines?

- Yes → *Stephanopyxis turris*

- No → *Melosira moniliformis*

(image by M. Himemiya)

No → Cells linked together with numerous visible spines?

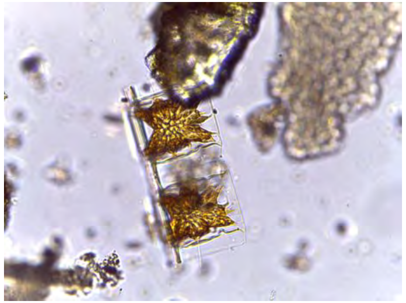
- Yes → *Skeletonema costatum*

- No → Cells connected by visible thread, like a string of beads?
  - Yes → Go to p.16
  - No → Go to p.17

Chloroplasts within the cells are arranged in a star-like shape?

Yes

Lithodesmium undulatum



No

Cells are touching?

Yes

Porosira sp.

No

Thalassiosira nordenskioeldii

Cells connected such that they look like a stack of Oreo cookies?

Yes → *Paralia sulcata*

No → Cell on the end of chain has tiny “teeth”?

- Yes → *Lauderia confervacea*
- No → Cells are touching from edge to edge?
  - Yes → *Leptocylindrus danicus*
  - No → Cells are touching only at the center of the cells? → *Lauderia* sp.

Paralia sulcata

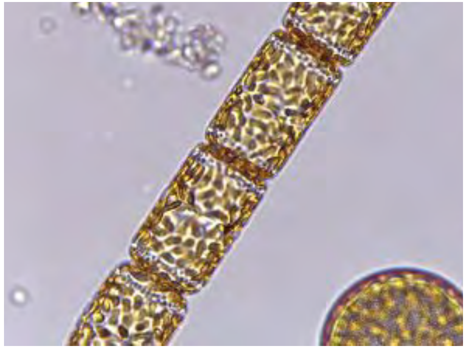
(image by G. Hannach)

Lauderia confervacea

(image by A-T. Skjevik)

Leptocylindrus danicus

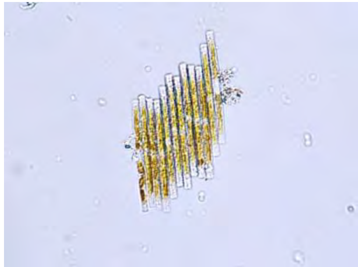
Lauderia sp.



Cells stacked together like a pile of books and are moving?

Yes

Bacillaria paxillifer



No

Cells linked together at one end, creating a fan shape?

Yes

Thalassiothrix sp.

No

Cells linked together in a zig-zag chain?

Yes

Synedra nitzschioides

No

Rectangular cells in a twisted chain?

Yes

Heliotheca tamesis

Taxonomic List of Species

Domain: Eukarya
- Kingdom: Chromista
  - Phylum: Myzozoa
    - Class: Dinophyceae
      - Order: Dinophysiales
        - Family: Dinophysaceae
          - Genus: ***Dinophysis***
      - Order: Gonyaulacales
        - Family: Ceratiaceae
          - Genus: *Tripos*
            - Species: ***T. furca***
              - ***T. fusus***
              - ***T. gibberus***
              - ***T. lineatus***
              - ***T. muelleri***
        - Family: Gonyaulacaceae
          - Genus: ***Gonyaulax***
      - Order: Gymnodiniales
        - Family: Gymnodiniaceae
          - Genus: ***Gymnodinium***
        - Family: Polykrikaceae
          - Genus: *Polykrikos*
            - Species: ***P. kofoidii***
      - Order: Noctilucales
        - Family: Noctilucaceae
          - Genus: *Noctiluca*
            - Species: ***N. scintillans***
      - Order: Peridiniales
        - Family: Peridiniaceae
          - Genus: ***Peridinium***
        - Family: Protoperidiniaceae
          - Genus: ***Protoperidinium***
      - Order: Prorocentrales
        - Family: Prorocentraceae
          - Genus: ***Prorocentrum***
      - Order: Pyrocystales
        - Family: Pyrocystaceae
          - Genus: ***Pyrocystis***

Taxonomic List of Species

Domain: Eukarya
- Kingdom: Protista
  - Phylum: Chrysophyta
    - Class: Bacillariophyceae
      - Order: Biddulphiales
        - Suborder: Biddulphiineae
          - Family: Chaetocerotaceae
            - Genus: *Chaetoceros*
              - Species: ***C. curvisetus***
                - ***C. debilis***
                - ***C. decipiens***
                - ***C. didymus***
                - ***C. socialis***
          - Family: Eupodiscaceae
            - Genus: *Isthmia*
              - Species: ***I. nervosa***
            - Genus: *Odontella*
              - Species: ***O. aurita***
          - Family: Hemiaulaceae
            - Genus: *Eucampia*
              - Species: ***E. striata***
                - ***E. zodiacus***
          - Family: Lithodesmiaceae
            - Genus: *Ditylum*
              - Species: ***D. brightwellii***
            - Genus: *Heliotheca*
              - Species: ***H. tamesis***
            - Genus: *Lithodesmium*
              - Species: ***L. undulatum***

Taxonomic List of Species

Domain: Eukarya
Kingdom: Protista
Phylum: Chrysophyta
Class: Bacillariophyceae
Order: Biddulphiales
Suborder: Coscinodiscineae
Family: Asterolampraceae
Genus: ***Asteromphalus***
Family: Coscinodiscaceae
Genus: *Coscinodiscus*
Species: ***C. oculus-iridis***
Family: Leptocylindraceae
Genus: *Corethron*
Species: ***C. pennatum***
Genus: *Leptocylindrus*
Species: ***L. danicus***
Family: Melosiraceae
Genus: *Melosira*
Species: ***M. moniliformis***
Genus: *Paralia*
Species: ***P. sulcata***
Genus: *Stephanopyxis*
Species: ***S. turris***
Family: Thalassiociraceae
Genus: ***Lauderia***
Species: ***L. confervacea***
Genus: ***Porosira***
Genus: *Skeletonema*
Species: ***S. costatum***
Genus: *Thalassiosira*
Species: ***T. nordenskioeldii***
T. subtilis
Suborder: Rhizosoleniineae
Family: Rhizosoleniaceae
Genus: *Rhizosolenia*
Species: ***R. semispina***

Taxonomic List of Species

- Domain: Eukarya
  - Kingdom: Protista
    - Phylum: Chrysophyta
      - Class: Bacillariophyceae
        - Order: Bacillariales
          - Suborder: Bacillariineae
            - Family: Bacillariaceae
              - Genus: *Bacillaria*
                - Species: ***B. paxillifer***
              - Genus: ***Nitzschia***
                - Species: ***N. closterium***
                - ***N. longissima***
              - Genus: ***Pseudo-nitzschia***
            - Family: Naviculaceae
              - Genus: ***Amphiprora***
              - Genus: ***Navicula***
                - Species: ***N. challengeri***
              - Genus: ***Pleurosigma***
          - Suborder: Fragilariineae
            - Family: Fragilariaceae
              - Genus: *Asterionella*
                - Species: ***A. japonica***
              - Genus: *Synedra*
                - Species: ***S. nitzschioides***
            - Family: Thalassionemataceae
              - Genus: ***Thalassiothrix***
        - Order: Triceratiales
          - Family: Triceratiaceae
            - Genus: *Hobaniella*
              - Species: ***H. longicruris***
            - Genus: ***Triceratium***
            - Genus: *Trieres*
              - Species: ***T. mobiliensis***

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Appendix D:

Open-source phytoplankton taxonomy websites:

- AlgaeBase: https://www.algaebase.org/
- California Academy of Sciences Catalogue of Diatom Names: http://researcharchive.calacademy.org/research/diatoms/names/index.asp
- Diatom Base: https://www.diatombase.org/aphia.php?p=searh
- Diatoms: https://www.ucl.ac.uk/GeolSci/micropal/diatom.html
- Diatoms of North America: https://diatoms.org/
    - Glossary (helpful for taxonomy terms): https://diatoms.org/glossary
- Kudela Lab at the University of California Santa Cruz: http://oceandatacenter.ucsc.edu/PhytoGallery/index.html
- Lucidcentral Identification and Diagnostic Tools - Antarctic Marine Diatoms: https://keys.lucidcentral.org/keys/v3/australian-antarctic-division/antarctic_marine_diatoms.html
- Monterey Bay weekly phytoplankton sampling: http://oceandatacenter.ucsc.edu/PhytoBlog/
- Nordic Microalgae and Aquatic Protozoa: http://nordicmicroalgae.org/taxon/Bacillariophyta
- PhycoKey from University of New Hampshire: http://cfb.unh.edu/phycokey/phycokey.htm
- Phyto'pedia - The Phytoplankton Encyclopaedia Project, The University of British Columbia: https://www.eoas.ubc.ca/research/phytoplankton/
- PlanktonNet (photo database): https://planktonnet.awi.de/index.php?contenttype=image_details&itemid=59862#content
- Tree of Life Web Project: http://tolweb.org/Diatoms/
- WoRMS - World Register of Marine Species: http://www.marinespecies.org/index.php