

Calcareous nannofossils from the Eocene North Atlantic Ocean (IODP Expedition 342 Sites U1403-1411)

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Abstract

Integrated Ocean Drilling Program Expedition 342 (June-July 2012) cored nine sites and 18 holes (Sites U1403-U1411) on the J-Anomaly and the Southeast Newfoundland ridges in the NW Atlantic Ocean. These sites recovered sections ranging from Pleistocene to upper Albian, but the expedition particularly focussed on the recovery of expanded Paleogene successions with high quality microfossil preservation. This was achieved by choosing sites with thick packages of drift-type sediments on topographic highs that would maximise the preservation of carbonate. The expedition succeeded in recovering middle Eocene to lower Oligocene and upper Oligocene to lower Miocene high sedimentation rate sediment sequences with very well preserved microfossils. Highlights of the expedition include the recovery of continuous Eocene/Oligocene and Oligocene/Miocene boundaries, a Cretaceous-Paleogene boundary section with intact spherule layer, and Cenomanian/Turonian section with a 44 cm black shale. Here, we describe notable aspects of the Eocene nannofossil record, including the exceptional preservation and the evolution of several important Eocene groups: *Nannotetrina*, the *Sphenolithus furcatolithoides* group, the *Reticulofenestra bisecta* group and the *Coccolithus gigas* group. We also present a taxonomic overview of the Eocene nannofossil assemblages from Sites U1403-1411, illustrating 164 taxa and describing 25 new species (*Blackites friedrichii*, *Blackites sextonii*, *Blackites subtilis*, *Calcidiscus scullyae*, *Clausicoccus norrisii*, *Coccolithus hulliae*, *Coccolithus opdykei*, *Cruciplacolithus nishii*, *Helicosphaera prolixa*, *Holodiscolithus agninae*, *Holodiscolithus lippertii*, *Holodiscolithus liuii*, *Holodiscolithus whitesideae*, *Nannotetrina plana*, *Nannotetrina ruda*, *Neococcolithes purus*, *Neococcolithes radiatus*, *Pontosphaera brinkhuisii*, *Pontosphaera hollisii*, *Pontosphaera romansii*, *Pontosphaera wilsonii*, *Reticulofenestra magniscutum*, *Scyphosphaera interstincta*, *Semihololithus pseudobiskayae*, *Syracosphaera octiforma*) and five new combinations (*Blackites inversus*, *Pontosphaera zigzag*, *Reticulofenestra erbae*, *Reticulofenestra isabellae*, *Umbilicosphaera elliptica*).

Keywords Paleogene, Eocene, Oligocene, Atlantic, taxonomy, calcareous nannofossils

1. Introduction

Integrated Ocean Drilling Program Expedition (IODP Exp.) 342 (June-July 2012) cored nine sites and 18 holes (Sites U1403-U1411; Figure 1) on the J-Anomaly and Southeast Newfoundland ridges in the NW Atlantic Ocean, recovering a virtually complete composite section ranging from upper Albian to Pleistocene, representing 100 Ma of Earth history (Figure 2). The youngest 15 million year portion of this record (middle Miocene to Recent) is typically represented by thin Pleistocene foraminifer-rich sandy clay, and thin, stratigraphically-short, sections of Pliocene and upper Miocene clay, often with manganese nodules. Below the middle Miocene, the stratigraphic histories of the sites fall into two distinct groups, corresponding to the J-Anomaly ridge and Southeast Newfoundland ridge (SENR) locations.

The J-Anomaly sites typically comprise high sedimentation-rate lower Miocene to upper Oligocene sequences, with occasional minor hiatuses, and lower sedimentation-rate Oligocene to Paleocene sequences. The lower Eocene to Paleocene sequence is relatively condensed (Site U1406) and/or contains one or two minor hiatuses (Site U1403 and U1406). Complete Miocene-Oligocene boundary sections were recovered at sites U1404 through U1406, and complete but lower sedimentation rate Oligocene-Eocene boundary sections at Site U1404 and U1406. Site U1403 is the deepest site on J-Anomaly ridge and recovered a lower Eocene through upper Cretaceous sequence, with several key intervals, including the early Eocene thermal maximum (ETM)-2, Paleocene-Eocene thermal maximum (PETM) and Cretaceous-Paleogene (K-Pg) boundary event (Figure 2).

The SENR sites comprise short Pleistocene and Neogene sequences lying over higher sedimentation-rate Oligocene through Paleocene sections. The highest sedimentation-rate, clay-rich drift sediments include middle Eocene sections at sites U1408 through U1410, and an upper Eocene through Oligocene section at Site U1411. These clay-rich sediments contain exceptionally well-preserved calcareous microfossils, including glassy planktic foraminifers and a diverse range of fragile and small nannoplankton. The carbonate-rich lower Eocene lithologies contain less well-preserved calcareous microfossils but nevertheless provide a relatively continuous stratigraphic record. PETM-equivalent sequences are present at sites U1407 and U1409, but the stratigraphy is condensed and/or includes minor hiatuses and, in the core of the event interval, the sediments are indurated, silicified and include chert beds. Site

U1407 also recovered a long Cretaceous sedimentary record, from the upper Maastrichtian to upper Albian, although a relatively large hiatus cuts out the lower Maastrichtian and upper Campanian. Sedimentation rates are low (0.15-0.41 cm/k.y.) but there is a relatively continuous record from the lower Campanian through upper Albian, including a striking Cenomanian/Turonian boundary black shale sequence, representing Oceanic Anoxic Event 2, and an Albian-Cenomanian section lying over shallow-water carbonate facies (Figure 2).

Initial biostratigraphic results are published in Norris *et al.* (2014) and high resolution integrated stratigraphic, isotopic and palaeoecological studies are in progress. In this paper, we describe some notable aspects of the Eocene nannofossil record, including the exceptional preservation and the evolution of several important Eocene groups: *Nannotetrina*, the *Sphenolithus furcatolithoides* group, the *Reticulofenestra bisecta* group and the *Coccolithus gigas* group. We also provide a taxonomic overview of the Eocene nannofossil assemblages from Sites U1407-1411, illustrating c.150 taxa and including the description of 25 new species and five new combinations.

2. Material and methods

Nannofossils were viewed in simple smear-slides (Bown and Young, 1998), using transmitted-light microscopy (Zeiss Axiophot) in cross-polarised (XPL) and phase-contrast (PC) light at x1000-1600. Selected samples were also examined in the scanning electron microscope (SEM: JEOL Digital JSM-6480LV) in order to confirm the high quality preservation that is evident in the light microscope (LM). Here we report on the middle Eocene through lower Oligocene sections from sites 1407 through 1411, which include the best preserved Paleogene nannoplankton.

3. Biostratigraphy

Semi-quantitative biostratigraphic data were generated during Exp. 342 and initial results are given in Norris *et al.* (2014), including range charts. In the Paleogene part of the section the nannofossil biozonation of Martini (1971) was used and the Exp. 342 timescale, based on Gradstein *et al.* (2012), is applied herein (see Norris *et al.*, 2014, fig. F5)

4. Exceptional microfossil preservation in clay-rich drift sediments

One of the primary objectives of Exp. 342 was the recovery of high accumulation rate, clay-rich sediments containing well-preserved microfossils suitable for geochemical and microfossil assemblage studies. Where drift sediments were recovered, we observed calcareous microfossil preservation that was good and moderate to good, and significantly better than the quality of preservation that is typical of most Paleogene deep-sea deposits. Furthermore, significant intervals of these drift successions contained exceptionally preserved calcareous microfossils, including diverse, minute and fragile calcareous nannofossils (see Plates 1-15 herein) and glassy planktic foraminifera (Norris *et al.*, 2014, Fig. F36). Such high quality preservation is usually only found in clay-rich hemipelagic shelf successions and the recovery of stratigraphically-continuous and expanded middle Eocene through lower Miocene successions with exceptional microfossil preservation was a significant success of the expedition.

5. Expedition 342 nannofossil occurrences: preservation or ecology?

The recent discovery of many new Paleogene taxa in the Tanzanian microfossil lagerstätte has led to re-evaluation of the taphonomic and ecological processes governing the preserved fossil record of calcareous nanoplankton (Bown *et al.*, 2008; Dunkley Jones *et al.*, 2009). The contrasting shelf and ocean distribution records of many nannofossil taxa, being rare or absent in deep-sea sediments and common and/or diverse in hemipelagic successions, can be interpreted as predominantly a taphonomic signal, an ecological signal, or some combination of both factors (Bown *et al.*, 2008). The Tanzanian lagerstätte is characterised by high abundances and/or diversity of Braarudosphaeraceae, Pontosphaeraceae, Rhabdosphaeraceae (especially *Blackites*), holococcoliths (e.g., *Clathrolithus*, *Holodiscolithus*, *Lanternithus*), and rarer occurrences of deep-time representatives of Calciosoleniaceae (*Calciosolenia*), Syracosphaeraceae (*Syracosphaera*) and abundant *Gladiolithus*. In addition, hemipelagic sediments tend to contain far greater numbers of very small (<3 μ m) coccoliths, which are often numerically dominant (e.g., Gibbs *et al.*, 2006; Dunkley Jones *et al.*, 2008; Bown, 2016; this work). Disentangling which is the prevalent control on these distributions is difficult because the majority of deep-sea sediments are either carbonate-rich or have undergone dissolution, and are therefore rarely free from the overprint of strong diagenetic modification processes. The Exp. 342 sites provide new insight into this problem because the incorporation of a significant clay component has resulted in the accumulation of hemipelagic-like sediments with improved preservation potential but in a truly oceanic setting (3.0-4.0km current depth; 2.6-3.1km palaeo-depth at 50 Ma). Through much of the Paleogene and lower Neogene succession we are able to

dismiss dissolution and overgrowth as a major factor controlling the presence or absence of nannofossils, and so the predominant factor on distribution is most likely the result of ecology. It should also be noted that there is little evidence of any significant microfossil reworking through these successions.

Braarudosphaeraceae. Braarudosphaeraceae is one group in which there is a relatively straightforward explanation for their strongly skewed shelf-sea distribution, because both extant and fossil forms are almost exclusively neritic, with rare oceanic occurrences explained by atypical events or environmental conditions (e.g. Kelly et al., 2003). This is confirmed in the Exp. 342 sites, which are virtually devoid of braarudosphaerids, with the exception of:

1. a short mid-Cretaceous interval (Albian-Cenomanian) with *Braarudosphaera africana* at Site 1407 where shallow water, initially reefal, conditions occurred early in the site's history;
2. very rare occurrences of *Braarudosphaera bigelowii* in the post-K/Pg mass extinction recovery interval at Site 1403; and
3. a short interval, at the Oligocene/Miocene boundary of Site 1405, which represents a period of unusual conditions with common *Braarudosphaera* and *Micrantholithus* (see Norris et al. 2014 for further details).

Holococcoliths. In general, the Exp. 342 holococcoliths are not as common or diverse as seen in the Tanzanian succession (Plates 10, 15), suggesting environmental factors play a role in their oceanic distribution. In this case, this may reflect the higher latitude position of the NW Atlantic area, or, alternatively, the outer shelf setting of Tanzania may have been richer in holococcoliths than the open-ocean. There are one or two exceptions to this, however, with *Zygrhablithus bijugatus* common through much of the Eocene succession, as it is in many other oceanic sites, confirming its widespread distribution in shelf and oceanic successions alike (Schneider et al., 2011; Gibbs et al., 2016). Also, *Daktylethra unitatis* is present through the Exp. 342 middle to upper Eocene, and ranges into the lower Miocene, extending the stratigraphic range of this taxon considerably. *Lanternithus minutus*, which is common in Tanzania, is only sporadically present at the Exp. 342 sites and never common.

Rhabdosphaeraceae. The occurrence of rhabdololiths in the Exp. 342 material is comparable to the Tanzania succession, with several taxa common and consistently present, e.g. *Blackites*

amplus, *B. tenuis*, *B. stilus* and *B. spinosus*. At least 12 of the 15 new rhabdolith taxa described from this stratigraphic interval in Tanzania (Bown, 2005; Bown and Dunkley Jones, 2006), are also present in the NW Atlantic (*B. bullatus*, *B. flammeus*, *B. furvus*, *B. fustis*, *B. globulus*, *R. gracilenta*, *B. kilwaensis*, *B. ornatus*, *B. rotundus*, *B. stilus*, *B. tortilis* and *B. virgatus*) and three more species are described herein (see below and Plates 8, 9, 15). This indicates that the rhabdolith group in general was broadly distributed in the Eocene with neritic and oceanic occurrences.

Small coccoliths. The link between preservation of small coccoliths and taphonomy is clearly demonstrated by comparison of modern taxa with the Holocene fossil record, which typically lacks coccoliths with length $<3\mu\text{m}$ (Young et al., 2005). When high quality nannofossil preservation is encountered in the fossil record then the presence of abundant, very small coccoliths is usually striking (Bown et al., 2008). This is confirmed in the Exp. 342 material, in which small coccoliths ($<3\mu\text{m}$) are dominant where preservation is good. In the middle Eocene to lower Oligocene interval, these coccoliths are predominantly reticulofenestrads, which typically make up ~50-60% of the assemblage (see, e.g., Plate 13, figs 1-6). Small representatives of coccolithaceans (e.g. *Coccolithus*, *Clausicoccus*) may also be common (Pl. 13, fig. 21; Pl. 14, fig. 9).

Other taxa. Other assemblage characteristics that are comparable with the Tanzania successions include high diversities in *Pontosphaera*, *Scyphosphaera* (Plates 6, 14) and *Helicosphaera* (Plates 5, 14) (six new species described herein), and the consistent occurrence of Eocene representatives of *Calcidiscus* and *Umbilicosphaera* (Plate 4).

6. Evolution of the genus *Nannotetrina*

Nannotetrina is a short-lived, middle Eocene nannofossil genus comprising around six species that are typically large, three-dimensional nannoliths with square, cruciform or stellate outline and four diagnostic raised ridges or crossbars (see Fig. 3 and Plate 7). In cross-polarized light the nannoliths are typically dark yellow to brown, indicating construction from few crystal units (at least four) that share high-angled c-axis crystallographic orientation, i.e., the elements are in extinction when lying flat. The unusual morphology of *Nannotetrina* has led to a number of different suggestions for their origin, ranging from nannolith ancestors, such as *Micula*, to more straightforward origins within Eocene coccolith groups, particularly from within the

Zygodiscaceae. Several authors have discussed the Zygodiscaceae ancestry (Bramlette and Sullivan, 1961; Perch-Nielsen, 1985) and specifically that they originated as modified, enlarged central-area crossbar structures from which the coccolith rim has been lost. Thickened and elevated crossbars are seen in both *Neococcolithes* and *Chiphragmalithus* in the stratigraphic interval preceding the appearance of the first *Nannotetrina* in Zone NP14 and so there is good stratigraphic support for this hypothesis. *Nannotetrina* also have comparable crystallography to the crossbars of *Neococcolithes* and *Chiphragmalithus*, i.e., they have high-angle c-axes. Unfortunately, the *Chiphragmalithus* group is poorly documented and stratigraphic ranges are not well constrained, but they are reported from Zone NP12 to NP14 (Bramlette and Sullivan, 1961; Shamrock and Watkins, 2012).

The link to the Cretaceous genus *Micula* was proposed by Romein (1979) and further discussed in Perch-Nielsen (1985) but there is little to support the idea as it is based on the erroneous observation that *Micula* ranged consistently through the Paleocene-Eocene, whereas these occurrences are now considered to be reworking. Further, the cubiform morphology of *Micula* is only very superficially similar to *Nannotetrina*, with *Micula* structure comprising far more numerous and complexly-intergrown crystal units with variable crystallographic orientations (see for example *Nannotax*: <http://ina.tmsoc.org/Nannotax3/link.php?taxon=Micula>).

Expedition 342 nannofossil assemblages from Subzone NP14a include a range of morphotypes that appear to represent transitional forms between *Neococcolithes/Chiphragmolithus* and *Nannotetrina* (Fig. 3 and Plate 7). These assemblages include *Neococcolithes protenus* coccoliths with typical simple, narrow, murolith rim and simple diagonal crossbars with all parts in near extinction in cross-polarized light (the R-unit proximal wall unit is very reduced in *Neococcolithes* and not visible in plan view in LM) (Pl. 7, figs 2-3). Alongside these forms are *Chiphragmolithus*-like coccoliths and *Nannotetrina*-like liths, which appear to represent transitional forms, as follows:

- 1) *Chiphragmolithus acanthodes* (Pl. 7, figs 4-12) – *Neococcolithes*-like but higher and larger with ragged outlines and crossbars that extend across the rim to the coccolith edge;
- 2) *Chiphragmolithus calathus* (Pl. 7, figs 13-15) - high and broadly-elliptical with high crossbars;
- 3) *Nannotetrina ruda* sp. nov. (Pl. 7, figs 16-20) - high, broad crossbars with reduced coccolith rim; and

4) *Nannotetrina plana* sp. nov. (Pl. 7, figs 21-30) - relatively flat with broad crossbars and a basal disc/rim.

This proliferation of morphologies occurs over a relatively short stratigraphic interval, immediately preceding the appearance of typical *Nannotetrina cristata* specimens (an elevated nannolith with four, relatively short crossbars/ridges that widen towards their ends and sit on a basal, plate-like structure: Pl. 7, figs 31-43), although several forms do continue alongside *Nannotetrina* through the upper part of Zone NP14. The transition from *Chiphragmolithus* to *Nannotetrina* thus appears to have been associated with a radiation in *Neococcolithes/Chiphragmolithus* coccoliths that include forms with *Nannotetrina* characters, such as reduction and loss of the muralith rim, lateral and vertical expansion of the crossbars and formation of a basal structure. In some of the early *Nannotetrina* forms, multiple elements are evident in the basal disc in LM (e.g. Pl. 7, figs 31-36), but this is not obvious in the younger *Nannotetrina* specimens. The radiation also includes *Chiphragmalithus*-like coccoliths such as *C. acanthodes* that may be related to the *Chiphragmalithus* species described from the older Zone NP12 interval, but perhaps more likely represent homeomorphs within the *Neococcolithes* lineage. The disarticulated crossbars of *Chiphragmalithus/Neococcolithes* coccoliths are also documented from this stratigraphic interval (e.g. Bown and Dunkley Jones, 2012) and these may account for older records of small '*Nannotetrina*' (e.g., Bralower and Mutterlose, 1995).

After the appearance of *N. cristata* in Subzone NP14b a number of specimens were observed that show relict coccolith-rim and crossbar-like structures at the base of the larger cruciform nannolith (Pl. 7, figs 37-43, indicated by arrows on the images), providing further support for these nannoliths being highly modified coccoliths that have lost much of or their entire coccolith rim. In these specimens, the relict rims are far smaller in diameter than the main cross structure. In later species of *Nannotetrina*, e.g., *N. fulgens*, the crossbars become very long and form free-rays with reduced basal structure or inter-arm fill (Pl. 12, fig. 12). In other species, such as, *N. spinosa* and *N. pappii*, additional ridges become prominent, giving the nannoliths a stellate appearance (Pl. 7, fig. 44).

7. Evolution of large middle Eocene Coccolithaceae

The middle Eocene is characterized by the occurrence of particularly large (>12 μm) coccolithacean coccoliths (see examples shown in Plates 3 and 12), which have been included in a number of different genera including *Coccolithus*, *Chiasmolithus*, *Crucioplacolithus* and

Birkelundia. The generic assignment has been particularly influenced by the relative importance placed upon central area structures, although modern representative of *Coccolithus* may develop both transverse and axial crossbars. The middle Eocene forms with wide central areas, relatively narrow tube cycles and diagonal crossbars are clearly correctly grouped within *Chiasmolithus* (e.g. *C. grandis*, *C. expansus*: Pl. 3, figs 27-29; Pl. 12, fig. 4) but the generic affinity of other species is less clear cut. One group most-closely resembles *Coccolithus*, with relatively narrow central-areas and broad tube-cycles but they have crossbars, usually axial, more rarely rotated. Although these taxa have sometimes been included within *Cruciplacolithus*, they are now more frequently classified as *Coccolithus* (e.g. *Coccolithus mutatus*, *Coccolithus staurion*). The distinctive marker species, '*Chiasmolithus*' *gigas* also appears to be one of these forms (original described as *Coccolithus*, but subsequently reassigned based on the presence of diagonal crossbars) and this is supported by new observations from the Exp. 342 material (Plate 3). These reveal a range of morphologies comprising a lineage with early forms having broad, axial crossbars (assigned to *C. staurion* herein: Pl. 3, figs 5-11) that give rise to coccoliths with rotated, asymmetric crossbars (named *C. cf. C. gigas* herein: Pl. 3, figs 12-20, 23-24) and then to forms with diagonal crossbars that characterise *C. gigas* (Pl. 3, figs 21-22, 25-26). The very large forms with axial and asymmetric crossbars, first appear near the Zone NP14-15 boundary, preceding the appearance of *C. gigas sensu stricto*, which marks the base of Subzone NP15b. This lineage strongly suggests that the '*Chiasmolithus*' genus, as currently used, is polyphyletic and the species *gigas* is reinstated to its original genus, *Coccolithus*, herein.

In addition to these very large forms, the middle Eocene assemblages also contain a diverse range of large *Coccolithus* coccoliths, including forms with crossbars (*C. hulliae* sp. nov., *C. opdykei* sp. nov.) and tranverse bars (*C. bipartoperculatus*).

8. Evolution of the *Sphenolithus furcatolithoides* group

Sphenolithus furcatolithoides are highly distinctive middle Eocene sphenoliths (Zones NP15b-NP16) with spines that bifurcate but remain roughly parallel before diverging again high-up on the spine (Plate 11). Shamrock (2010) showed that this highly distinctive species was preceded by forms with spines that diverge at a higher angle, low on the spine, calling the species *S. perpendicularis*. The excellent preservation of the Exp. 342 material reveals a wide range of different morphotypes within this group, including early spinose forms with very high-angle

narrow spines (*S. cf. S. perpendicularis* herein; Pl. 11, figs 1-3), a variety of *S. perpendicularis* types (Pl. 11, figs 7-13), and *S. furcatolithoides* variants with spines that converge or diverge at different angles high-up along the spine (Pl. 11, figs 15-21, 26). These spines can be extremely long, up to 25 μ m in length, and represent some of the ‘largest’ nannofossils ever found. The morphology of specimens close to the first appearance of *S. furcatolithoides* itself, suggest that it may have evolved from a *S. radians*-like ancestor, rather than the preceding widely-bifurcating forms (Pl. 11, fig. 14).

9. Evolution of the *Reticulofenestra bisecta* group

Reticulofenestrid coccoliths with closed central areas are known through most of this groups history (lower Eocene to Recent) but the appearance of common, medium- to large-sized forms with conspicuous (birefringent) distal, central-area ‘plugs’ (the *R. bisecta* group of Bown & Dunkley Jones, 2012; Pl. 2, figs 20-44) is a highly distinctive stratigraphic signal occurring in lowermost Zone NP17 (~40.36 Ma) and close to the onset of the Middle Eocene climatic optimum (MECO) event (Fornaciari et al., 2010). However, the discovery of very rare and unusual *R. bisecta*-like coccoliths in Subzone NP15 (from ~46 Ma) in the Exp. 342 material indicates that the group had a cryptic origination at least six million years earlier than this (Pl. 2, figs 25-44). These coccoliths, named *R. magniscutum* sp. nov. herein, have very unusual, thickened, dome-like distal shields but possess the distinctive central plug that is characteristic of the *R. bisecta* group.

It should be noted that this distinctive reticulofenestrid group includes *R. stavensis* (>10 μ m) and *R. bisecta* (<10 μ m) but that these species are also placed in a separate genus, *Dictyococcites*, by some authors, and different species names, e.g. *hesslandii* and *scrippsae*, and size categories are also applied (e.g. Agnini et al., 2014). In addition, reticulofenestrads with simple, closed central areas are also referred to as *R./D. bisecta* by some authors but we consider these to be separate taxa, though poorly defined in current classifications (see below for further discussion).

10. Systematic palaeontology

This section provides images of a representative selection of nannofossils from the IODP Exp. 342 Eocene sites (U1403-1411) in 12 LM plates and three SEM plates (Plates 13-15). The LM images are reproduced at constant magnification and a 2 μ m scale bar is provided beside at least

one of the images on each plate. Taxonomic comments are only provided for notable taxa and the description of 25 new species. The taxonomic listing refers only to species illustrated in the plates. Sample information is provided using standard IODP notation (Hole-Core-Section, depth in cm in section). The descriptive terminology (including size classes) follows the guidelines of Young *et al.* (1997). The higher taxonomy follows the scheme for extant coccolithophores of Young *et al.* (2003) and, for the extinct taxa, the scheme of Young & Bown (1997) and *Nannotax* (ina.tmsoc.org/Nannotax3). All new taxonomic names are Latin, unless stated otherwise, and the meaning is given in each case. Range information is given for stratigraphic distributions in the Exp. 342 sites, unless stated otherwise. Only bibliographic references not included in Perch-Nielsen (1985), Bown (1998) or Jordan *et al.* (2004) are included in the reference list. A comprehensive list of bibliographic references can also be found on *Nannotax*. The following abbreviations are used: LM – light microscope, XPL cross-polarised light, PC – phase-contrast illumination, L – length, H – height, W – width, D – diameter. Type material and images are stored in the Department of Earth Sciences, University College London.

PLACOLITH COCCOLITHS

Order ISOCHRYSIDALES Pascher, 1910

Family NOELAERHABDACEAE Jerkovic, 1970 emend. Young & Bown, 1997

Cyclicargolithus floridanus Group

Pl. 1, figs 20-27; Pl. 13, fig. 7. **Description:** Subcircular to broadly elliptical reticulofenestrids with narrow central area and thin, imperceptible net (non-birefringent or lost).

Cyclicargolithus cf. *C. abisectus* (Müller, 1970) Wise, 1973

Pl. 1, fig. 25. **Remarks:** Used here for rare, but conspicuous, very large, subcircular reticulofenestrids seen in the middle Eocene (e.g. Zone NP14) and similar in overall morphology to the younger, Oligocene, species *C. abisectus*.

Cyclicargolithus floridanus (Roth & Hay, in Hay *et al.*, 1967) Bukry, 1971

Pl. 1, figs 20-24; Pl. 13, fig. 7. **Remarks:** Used in a broad sense here for subcircular reticulofenestrids with narrow central area. Specimens with closed central areas are called *Cyclicargolithus* cf. *C. floridanus*.

Cyclicargolithus cf. *C. floridanus* (Roth & Hay, in Hay *et al.*, 1967) Bukry, 1971 Pl. 2, figs 6-12

Pl. 1, figs 26-27. **Remarks:** Like *C. floridanus* but with closed central area.

Cyclicargolithus luminis (Sullivan 1965) Bukry 1971 *sensu* Shamrock & Watkins, 2012 Pl. 1, figs 28-29. **Remarks:** A distinctive, birefringent circular coccolith occurring rarely in Zone NP14 to Subzone NP15a at sites 1407-1410. It is distinguished by relatively straight and axial extinction lines. Shamrock & Watkins (2012) discuss the differentiation between this and the older *Cyclicargolithus parvus* Shamrock & Watkins, 2012 species (previously called *C. luminis* in Bown, 2005).

***Reticulofenestra bisecta* Group**

Pl. 2, figs 20-44; Pl. 13, fig. 11. **Description:** Elliptical reticulofenestrids with central area closed by a robust, conspicuous distal ‘plug’ (birefringent). In the type upper Eocene specimens this plug is a distal structure that is underlain by a proximal coarse grill of near radial laths. Thus defined, the stratigraphic range of the group is middle Eocene to lowermost Miocene. We do not include reticulofenestrid coccoliths in which the central area is simply closed (e.g. see Pl. 1, figs 26-27; Pl. 2, figs 17-19, 24), although these taxa are poorly served by current reticulofenestrid nomenclature. Some authors consider these forms to be ecophenotypic variants (e.g., Young, 1990, 1998), while others apply a parallel taxonomy or broaden the taxonomic concept of taxa such as *bisecta*. **Included species:** *R. bisecta*, *R. filewiczii*, *R. magniscutum*, *R. stavensis*.

Reticulofenestra bisecta (Hay *et al.*, 1966) Roth, 1970

Pl. 2, figs 20-21; Pl. 13, fig. 11. **Remarks:** Less than 10 μ m in length (the holotype is 8 μ m).

Reticulofenestra filewiczii (Wise & Wiegand in Wise, 1983) Dunkley Jones *et al.*, 2009 Pl. 2, fig. 23. **Remarks:** Appears at the same time as other members of the *R. bisecta* group and is probably closely related to these forms, differing only in having a small central opening.

Reticulofenestra stavensis (Levin & Joerger, 1967) Varol, 1989 Pl. 2, fig. 22

Remarks: Greater than 10 μ m in length (the holotype is 14 μ m).

Reticulofenestra magniscutum sp. nov.

Pl. 2, figs 25-44. **Derivation of name:** From *magnus*, meaning ‘elevated’, and ‘*scutum*’ meaning shield, referring to the elevated distal shield of this species. **Diagnosis:** Large, elliptical reticulofenestrads with a thickened, dome-like distal shield and central area filled with a plug. **Differentiation:** Similar to other species of the *Reticulofenestra bisecta* group but with an elevated, dome-like distal shield, which is therefore highly birefringent (orange) in XPL and frequently seen in side view (Pl. 2, figs 41-44). **Remarks:** We have observed this species from a short stratigraphic interval in the middle Eocene (Subzone NP15a-lower Zone NP16), in an interval that predates the common occurrence of other members of the *Reticulofenestra bisecta* group by around 6 m.y. The species is very rare and so tracing the relationship between *R. magniscutum* and *R. bisecta* has not been possible. **Dimensions:** Holotype L = 8.5 μm (Paratype L = 9.0 μm). Side view coccolith height $\sim 6.5 \mu\text{m}$. **Holotype:** Pl.2, fig.25. **Paratype:** Pl.2, figs 31. **Type locality:** IODP Hole U1408A, NW Atlantic Ocean. **Type level:** Middle Eocene, Sample U1408A-14X-5, 63cm (Zone NP16). **Occurrence:** Rare. Subzone NP15a-Zone NP16; IODP Sites U1408, U1409 and U1410.

***Reticulofenestra reticulata* Group**

Pl. 2, figs 3-16; Pl. 13, figs 12-16. **Remarks:** Typically circular reticulofenestrads with circular central area spanned by robust, visible net (birefringent). We currently include *R. erbae* (closed central-area), *R. isabellae* ($>12\mu\text{m}$, broad tube-cycle and narrow central-area); *R. reticulata* ($<12\mu\text{m}$, broad tube-cycle and narrow central-area) and *R. westerholdii* (medium-sized with less conspicuous tube cycle and inconspicuous or no central net).

Reticulofenestra erbae Fornaciari *et al.*, 2010 comb. nov.

Pl. 2, figs 13-14; Pl. 13, fig. 12. **Basionym:** *Cribozentrum erbae* Fornaciari *et al.*, 2010, p. 251, pl. 2, fig. 1, *Stratigraphy*, 7: 229-264.

Reticulofenestra isabellae Catanzariti *et al.* in Fornaciari *et al.*, 2010 comb. nov.

Pl. 2, figs 11-12; Pl. 13, fig. 16. **Basionym:** *Cribozentrum isabellae* Catanzariti, Rio & Fornaciari in Fornaciari *et al.*, 2010, p. 252, pl. 2, fig. 4, *Stratigraphy*, 7: 229-264.

Reticulofenestra reticulata (Gartner & Smith, 1967) Roth & Thierstein, 1972

Pl. 2, figs 7-10; Pl. 13, figs 13-15. **Remarks:** Used in a broad sense here for circular reticulofenestrids with moderately-wide to narrow central areas and a visible net (birefringent). Very large forms ($>12\mu\text{m}$) have been differentiated as *R. isabellae* (Pl. 2, figs 11-12) by Fornaciari *et al.* (2010) and we informally differentiated forms with wide central areas (Pl. 2, figs 7-9) and specimens with subcircular to elliptical outlines (Pl. 2, figs 3-6). Further subdivision may be warranted.

Reticulofenestra westerholdii Bown & Dunkley Jones, 2012

Pl. 2, figs 15-16. **Remarks:** This species has an inconspicuous or no central net but is circular and is, in other respects, very similar to other species in the *R. reticulata* group.

***Reticulofenestra lockeri* Group**

Pl. 1, figs 30-43; Pl. 2, figs 1-2; Pl. 13, fig. 10. **Description:** Elliptical reticulofenestrids with relatively open central area and robust, visible net (birefringent).

Reticulofenestra daviesii (Haq 1968) Haq, 1971

Pl. 1, figs 33-36. **Remarks:** Differentiated from *R. lockeri* by a row of visible pores around the edge of the central net. Although this species becomes conspicuous and abundant around the Eocene/Oligocene boundary, it ranges down into the middle Eocene (Zone NP14) in the Exp. 342 material. **Occurrence:** Zone NP14-NP23.

Reticulofenestra lockeri Müller, 1970

Pl. 1, fig. 32; Pl. 13, fig. 10. **Occurrence:** Lower Eocene-lower Miocene (Zone NP13-NN2).

Reticulofenestra cf. *R. lockeri* Müller, 1970

Pl. 1, figs 30-31; Pl. 2, figs 1-2. **Remarks:** Indeterminate forms with central areas that are either narrower (Pl. 1, figs 30-31) or wider than the typical morphology (Pl. 2, figs 1-2).

Reticulofenestra macmillanii Dunkley Jones et al., 2009 Pl. 1, fig. 37

Reticulofenestra onusta (Perch-Nielsen, 1971) Wise, 1983

Pl. 1, figs 38-43. **Description:** Large to very large, distinctive elliptical reticulofenestrids with a wide central area spanned by a finely perforate, weakly birefringent net. **Differentiation:**

Distinguished from other *R. lockeri* group coccoliths by large size, wider central area and clearly visibly fine perforations across the net. **Dimensions:** L = ~11.0-12.5 μm . **Occurrence:** Rare, but apparently restricted to Subzones NP15b-c; IODP Sites U1409, U1410. Holotype from Zone NP15. Questionable occurrences in Zone NP16 at Site 1410.

***Reticulofenestra umbilicus* Group**

Pl. 1, figs 8-19, 44-48; Pl. 12, figs 1-3; Pl. 13, figs 8-9. **Description:** Elliptical reticulofenestrids with relatively-open central area and thin, imperceptible net (non-birefringent or lost).

Reticulofenestra dictyoda (Deflandre in Deflandre & Fert, 1954) Stradner in Stradner & Edwards, 1968

Pl. 1, figs 9-12; Pl. 13, fig. 8. **Remarks:** Used here in a broad sense for elliptical reticulofenestrids with elliptical and relatively open central areas.

Reticulofenestra hillae Bukry & Percival, 1971 Pl. 1, figs 44-45

Reticulofenestra minuta Roth, 1970

Pl. 1, fig. 8; Pl. 13, figs 1-4. **Remarks:** Used here in a broad sense for very small (<3 μm), elliptical reticulofenestrids. Although they typically have open central areas, in SEM many specimens are seen with closed central areas and at this size it may be difficult to distinguish the different varieties in LM. Our SEM observations suggest there is considerable diversity of form in this size range.

Reticulofenestra umbilicus (Levin, 1965) Martini & Ritzkowski, 1968 Pl. 1, figs 46-48; Pl. 12, figs 1-3; Pl. 13, fig. 9

Remarks: The first appearance of very large, >14 μm , elliptical reticulofenestrids (the species *R. umbilicus*) has long been used as a distinctive stratigraphic marker (e.g. Backman and Hermelin, 1986). In the Exp. 342 material these sizes are attained by subcircular to elliptical reticulofenestrids (similar to *R. wadeae* and *R. umbilicus*) in Subzone NP15b, around 3 m.y. prior to the level typically cited for this biohorizon. Agnini et al. (2014) suggest that the use of the first common occurrence of *R. umbilicus* may represent a more consistent horizon, above the last occurrence of *C. gigas*.

Reticulofenestra wadeae Bown, 2005 Pl. 1, figs 13-19

Family **PRINSIACEAE** Hay & Mohler, 1967 emend. Young & Bown, 1997

Girgisia Varol, 1989

Girgisia gammation (Bramlette & Sullivan, 1961) Varol, 1989 Pl. 1, figs 5-7

Genus *Toweius* Hay & Mohler, 1967

Pl. 1, figs 1-4. **Remarks:** *Toweius* was one of the dominant placolith groups of the late Paleocene to early Eocene but declined, broadly coincident with the appearance and rise of the reticulofenestrid group in the early Eocene (zones NP12-13) (e.g., Agnini et al. 2006). The extinction of *Toweius* has remained poorly constrained with reports ranging from Zone NP12 (Bralower and Mutterlose 1995) to Zone NP15 (Perch-Nielsen, 1985). Relatively common *Toweius* coccoliths were documented in equatorial Pacific sites up to Zone NP15 by Bown and Dunkley Jones (2012) and similarly we see *Toweius* through to Subzone NP15b in the Exp. 342 sites (e.g. Site 1409), confirming this later extinction level.

Toweius magnicrassus Bukry, 1971 Pl. 1, figs 3-4

Toweius pertusus (Sullivan, 1965) Romein, 1979 Pl. 1, fig. 1

Toweius patellus Bown, 2016 Pl. 1, fig. 2

Order COCCOLITHALES Haeckel, 1894 emend. Young & Bown, 1997

Family **COCCOLITHACEAE** Poche, 1913 emend. Young & Bown, 1997

Coccolithus biparteoperculatus (Varol, 1991) Bown & Dunkley Jones, 2012 Pl. 3, figs 30-31

Coccolithus crassus Bramlette & Sullivan, 1961 Pl. 2, figs 45-48

Remarks: Like *C. pelagicus* but with an unusually birefringent shield image in XPL.

Occurrence: upper Zone NP12-14a (Wei, 1993).

Coccolithus eopelagicus (Bramlette & Riedel, 1954) Bramlette & Sullivan, 1961 Pl. 12, fig.

5

Coccolithus formosus (Kamptner, 1963) Wise 1973 Pl. 13, figs 19-20

Coccolithus hulliae sp. nov.

Pl. 4, figs 7-17. **Derivation of name:** Named after Celli Hull (University of Yale, USA), Exp. 342 shipboard scientist, micropalaeontologist and palaeoceanographer. **Diagnosis:** Broadly elliptical coccolith with *Ericsonia*-like shield image and moderately wide central area (similar to shield width) spanned by conspicuous axial crossbars. **Remarks:** In XPL the shields appear similar to *Ericsonia* (i.e. with broad, bright tube cycle). Although *Ericsonia* coccoliths are rarely and sporadically seen through the Eocene, these are usually small, circular forms and we consider it most likely that this species arose from a *Coccolithus* ancestor. Appears to be stratigraphically restricted to Zones NP14-15 in the Exp. 342 material. This species may have been identified as *Ericsonia insolita* Perch-Nielsen, 1971 in Bralower and Mutterlose (1995) and documented as having a first appearance in Subzone NP14a. **Differentiation:** Distinguished from other *Coccolithus* and *Ericsonia* by its distinctive shield image in XPL and moderately wide central area with conspicuous axial crossbars. **Dimensions:** Holotype L = 8.4 μm (Paratype L = 8.6 μm). **Holotype:** Pl. 4, fig. 16. **Paratype:** Pl. 4, fig. 13. **Type locality:** IODP Hole U1407A, NW Atlantic Ocean. **Type level:** Middle Eocene, Sample U1407B-8-CC (Subzone NP14b). **Occurrence:** Subzone NP14b-15b; IODP Sites U1407, 1408 and 1409. Site 865, Pacific Ocean (Bralower and Mutterlose, 1995).

Coccolithus cf. *C. hulliae* sp. nov. var. 1

Pl. 4, figs 1-4. **Remarks:** Similar to *C. hulliae* but with a transverse bar. **Occurrence:** Subzone NP14b-15b; IODP Sites U1407 and U1409.

Coccolithus cf. *C. hulliae* sp. nov. var. 2

Pl. 4, figs 5-6. **Remarks:** Similar to *C. hulliae* but with a moderately wide, apparently vacant, central area (similar to shield width). **Occurrence:** Subzones NP15b-c; IODP Site U1408.

Coccolithus pauxillus Bown, 2010 Pl. 4, figs 29-30; Pl. 13, fig. 21

Coccolithus pelagicus (Wallich, 1877) Schiller, 1930 Pl. 13, figs 17-18

***Coccolithus gigas* Group**

Pl. 3, figs 1-26; Pl. 12 fig. 7. **Description:** Large to very large *Coccolithus* coccoliths with narrow to moderately-wide central areas spanned by crossbars that are conspicuous in light microscope. **Remarks:** These coccoliths have previously been variously classified within the

genera *Cruciplacolithus*, *Chiasmolithus* and *Coccolithus* but appear to represent a coherent lineage with stratigraphic range restricted to the mid-part of the Eocene (Zones 14-16). The inclusion of these species within the genus *Coccolithus* is consistent with the extant *Coccolithus* species, which can also produce central area bars and crosses. **Included species:** *C. gigas*, *C. mutatus*, *C. opdykei*, *C. staurion*.

Coccolithus opdykei sp. nov.

Pl. 3, figs 1-4. **Derivation of name:** Named after Bradley Opdyke (The Australian National University, Australia), Exp. 342 shipboard scientist and palaeoceanographer. **Diagnosis:** Large (<12 μ m) *Coccolithus* with a narrow central area (<shield width) spanned by a broad, birefringent, axial to near-axial crossbars that nearly fill the central area. **Differentiation:** Smaller than *C. mutatus*, *C. staurion* and *C. cf. C. gigas*, with broader crossbars than *C. mutatus* and *C. staurion*. Similar to *Cruciplacolithus opacus* Shamrock & Watkins, 2012 but with a broader and brighter tube cycle in XPL. **Dimensions:** Holotype L = 11.1 μ m (Paratype L = 9.6 μ m). **Holotype:** Pl. 3, fig. 2. **Paratype:** Pl. 3, fig. 1. **Type locality:** IODP Hole U1407A, NW Atlantic Ocean. **Type level:** Middle Eocene, Sample U1407A-8H-CC (Subzone NP14b). **Occurrence:** Subzones NP14b-15b; IODP Sites U1407 and U1409.

Coccolithus gigas Bramlette & Sullivan, 1961 emend.

Pl. 3, figs 21-22, 25-26; Pl. 12, fig. 7. **Emended diagnosis:** Very large *Coccolithus* with narrow to moderately wide central area spanned by thick crossbars which are diagonal or near diagonal in orientation, making an angle of 30° or greater with the longitudinal axis. **Differentiation:** Distinguished from *Coccolithus cf. C. gigas* by bar angles that are rotated greater than 30° from the longitudinal axis. Typically the longitudinal bar is closer to axial than diagonal in *Coccolithus cf. C. gigas*. **Occurrence:** Subzone 15b.

Coccolithus cf. C. gigas Bramlette & Sullivan, 1961

Pl. 3, figs 12, 15-17, 19-20, 23-24. **Description:** Very large *Coccolithus* with narrow to moderately wide central area spanned by thick crossbars which are rotated from axial by up to 29°. **Differentiation:** Distinguished from *C. gigas* by having near-axial to slightly rotated crossbars rather than diagonal or near-diagonal orientation, and from *C. mutatus* by the thicker crossbars. **Occurrence:** Subzones NP15a-b (rare, questionable specimens in NP14b and NP15c); IODP Sites U1407, U1408, U1409 and U14010.

Coccolithus mutatus (Perch-Nielsen, 1971) Bown, 2005

Pl. 3, figs 7, 13-14, 18. **Description:** Very large *Coccolithus* with moderately-broad central area spanned by narrow crossbars that are axial or near axial. **Occurrence:** Zone NP14b-16; sites U1407-U1410.

Coccolithus staurion Bramlette & Sullivan, 1961

Pl. 3, figs 5-6, 8-11. **Description:** Very large ($>12\mu\text{m}$) *Coccolithus* with narrow central area spanned by robust axial crossbars. **Remarks:** The paratype has narrow bars and is probably a *C. mutatus* specimen. The holotype is large in size (12-15 μm) and we distinguish smaller forms as *Coccolithus opdykei* sp. nov.. **Synonym:** *Coccolithus insolitus* (Perch-Nielsen, 1971) Ladner & Wise, 2002. **Occurrence:** Zone NP13-17; sites U1407-U1410.

***Chiasmolithus-Cruciplacolithus* Group**

Bramletteius serraculoides Gartner, 1969 Pl. 4, figs 18-20

Chiasmolithus expansus (Bramlette & Sullivan, 1961) Gartner, 1970 Pl. 3, figs 27-29

Chiasmolithus grandis (Bramlette & Riedel, 1954) Radomski, 1968 Pl. 12, fig. 4

Cruciplacolithus cruciformis (Hay & Towe, 1962) Roth, 1970 Pl. 4, fig. 21

Cruciplacolithus nishii sp. nov.

Pl. 4, figs 22-28. **Derivation of name:** Named after Hiroshi Nishi (Tohoku University, Sendai, Japan), Exp. 342 shipboard scientist and micropalaeontologist. **Diagnosis:** Medium sized *Cruciplacolithus* with narrow shields and wide central area spanned by narrow axial crossbars bearing a spine. **Differentiation:** Distinguished from other *Cruciplacolithus* by the wide central area and spine-bearing cross – an unusual feature amongst Cenozoic placoliths. **Dimensions:** Holotype L = 4.2 μm (Paratype L = 4.3 μm). **Holotype:** Pl.4 , fig. 27. **Paratype:** Pl.4, figs 24. **Type locality:** IODP Hole U1408A, NW Atlantic Ocean. **Type level:** Middle Eocene, Sample U1408A-4H-CC (Zone NP16). **Occurrence:** Zone upper NP16-17; IODP Site U1408, U1409.

***Clausicoccus* Group**

Pl. 4, figs 33-45; Pl. 14, figs 9-14. **Remarks:** A wide range of sizes is seen in this group from very small ($<3\mu\text{m}$, e.g. *Clausicoccus* sp. small, Pl. 14, fig. 9) to very large ($>12\mu\text{m}$, e.g.

Clausicoccus vanheckiae and *Clausicoccus norrisii*, Pl. 4, figs 38-43), but all are characterised by coccolithacean-type rims with narrow to relict distal tube cycles and a relatively coarse, distal, perforate central-area net. A number of SEMs suggests there is also a more finely perforate grill on the proximal side (Pl. 14, fig. 13).

Clausicoccus fenestratus (Deflandre & Fert, 1954) Prins 1979 Pl. 4, figs 35-36; Pl. 14, fig. 13

Clausicoccus fenestratus large (Deflandre & Fert, 1954) Prins 1979

Pl. 4, fig. 37. **Remarks:** Like *C. fenestratus* but large ($\sim > 9 \mu\text{m}$). Similar in size to *Clausicoccus vanheckiae* but with relatively broader rim and narrower central area with fewer perforations. These forms become conspicuous for a short stratigraphic interval in Zone NP17 in the Exp. 342 material.

Clausicoccus cf. *C. fenestratus* (Deflandre & Fert, 1954) Prins 1979

Pl. 4, figs 44-45. **Remarks:** Like *Clausicoccus fenestratus* but the central, perforate plate takes the form of broad axial crossbars.

Clausicoccus norrisii sp. nov.

Pl. 4, figs 40-43 **Derivation of name:** Named after Richard Norris (Scripps Oceanographic Institute, USA), Exp. 342 co-chief scientist, micropalaeontologist and palaeoceanographer.

Diagnosis: Large, broadly elliptical coccolithacean coccolith with broad shields and moderately wide central area (similar to shield width) spanned by a plate that is indistinctly perforate and crossed by strong diagonal extinction lines. The bright inner cycle is relatively indistinct. **Remarks:** Specimens of this species have previously been assigned to the species '*Coccolithites*' *cribellum* Bramlette & Sullivan 1961 and placed in the genera *Cruciplacolithus* and *Clausicoccus* (Prins, 1979; Romein, 1979). The holotype of *cribellum* has narrower shields and a strongly perforate plate and is probably closely allied to, or a junior synonym of, *Clausicoccus fenestratus*. **Differentiation:** Distinguished from other *Clausicoccus* by larger size, relatively wider shield and bright but indistinctly perforate central area plate. **Dimensions:** Holotype L = 12.7 μm (Paratype L = 10.6 μm). **Holotype:** Pl. 4, fig. 42. **Paratype:** Pl. 4, fig. 40. **Type locality:** IODP Hole U1407A, NW Atlantic Ocean. **Type level:** Middle Eocene, Sample U1407A-10-2, 100 cm (Subzone NP14a). **Occurrence:** Subzone NP14a; IODP Site U1407. Difficult to determine its range from published records,

which often combine *C. norrisii* and *C. fenestratus*. Reported as NP11-17 by Shamrock and Watkins (2012) for *C. fenestrata*-like specimens >10 μ m in length.

Clausicoccus subdistichus (Roth & Hay in Hay et al., 1967) Prins, 1979 Pl. 4, figs 33-34; Pl. 14, figs 11-12

Clausicoccus vanheckiae (Perch-Nielsen, 1986) de Kaenel & Villa, 1996 Pl. 4, fig. 38-39

Hughesius tasmaniae (Edwards and Perch-Nielsen, 1975) de Kaenel and Villa, 1996 Pl. 4, figs 31-32

Family **CALCIDISCACEAE** Young & Bown, 1997

Remarks: We follow the classification of Young and Bown (2014) by placing the majority of Paleogene calcidiscids with closed central-areas in *Calcidiscus* and those with open central-areas in *Umbilicosphaera*. The excellent preservation of the Exp. 342 material reveals the presence of many of the calcidiscid species described from the Tanzania lagerstätte.

Calcidiscus bicircus Bown, 2005 Pl. 4, figs 46-47

Calcidiscus gerrardii Bown, 2005 Pl. 4, figs 52-53

Calcidiscus henrikseniae Bown, 2005 Pl. 4, figs 54-57

Calcidiscus scullyae sp. nov.

Pl. 4, figs 48-51. **Derivation of name:** Named after Caitlin Scully (Scripps Institution of Oceanography, USA), Exp. 342 Education Officer. **Diagnosis:** Medium-sized, circular-subcircular placoliths with a non-birefringent distal shield, narrow, bright tube-cycle and narrow central-area spanned by low-birefringence crossbars. **Differentiation:** Similar to *C. bicircus* but with narrow central area spanned by crossbars (see also Bown, 2005, Pl. 9, figs 21-22). *Calcidiscus parvicrucis* Bown, 2005 is elliptical, has a more distinct tube cycle and a younger range (Lower Eocene). **Dimensions:** Holotype L = 6.3 μ m (Paratype L = 6.0 μ m). **Holotype:** Pl. 4, fig. 42. **Paratype:** Pl. 4, fig. 40. **Type locality:** IODP Hole U1407A, NW Atlantic Ocean. **Type level:** Middle Eocene, Sample U1407B-8-CC (Subzone NP14b). **Occurrence:** Subzone NP14b; IODP Site U1407 (also Tanzania TDP Site 2; Bown, 2005).

Umbilicosphaera bramlettei (Hay & Towe, 1962) Bown et al., 2007

Pl. 5, figs 7-9; Pl. 14, figs 7-8. **Remarks:** *U. bramlettei* varies significantly in size through the Eocene and here we distinguish a large variant, with diameter typically greater than 7.5 μm . These large coccoliths are very similar to the image named as *Coronocyclus prionion* by Shamrock and Watkins (2012), defined therein as being $>7.5 \mu\text{m}$, but the holotype of *prionion* has a strongly serrated outline and appears to be a *Coronocyclus* coccolith.

Umbilicosphaera detecta (de Kaenel & Villa, 1996) Young & Bown, 2014 Pl. 5, fig. 10

Umbilicosphaera elliptica (Shamrock & Watkins, 2012) comb. nov.

Pl. 5, figs 1-3. **Basionym:** *Calcidiscus ellipticus* Shamrock & Watkins, 2012, p. 25, pl. 1, fig. 13. *Stratigraphy*, 9: 1-54. **Remarks:** Following Young and Bown (2014), we place this calcidiscid with open, central area within *Umbilicosphaera*. **Occurrence:** Reported as NP14a-21 in Shamrock and Watkins (2012), we only found unequivocal forms in Subzone NP14b. This morphology is also similar to that seen in *Bramletteius serraculoides* and *Umbilicosphaera detecta*.

Umbilicosphaera protoannula (Gartner, 1971) Young and Bown, 2014 Pl. 5, figs 4-6

Placolith coccoliths *Incertae Sedis*

Birkelundia arenosa Perch-Nielsen, 1971 Pl. 5, figs 11-14

Ellipsolithus lajollaensis Bukry & Percival, 1971 Pl. 5, figs 16-17

Markalius latus Shamrock & Watkins, 2012

Pl. 5, fig. 27. **Remarks:** Large *Markalius* (5.5-9.1 μm) with a wide birefringent cycle occupying $>33 \%$ of the coccolith diameter (Shamrock and Watkins, 2012). **Occurrence:** NP9/10-14b according to Shamrock and Watkins (2012).

Pedinocyclus annulus Shamrock & Watkins, 2012 Pl. 5, figs 20-25

Remarks: Medium to large elliptical placolith with a bright inner cycle and open central area. **Occurrence:** Subzone NP14b-21 according to Shamrock and Watkins (2012).

Tetralithoides symeonidesii Theodoridis, 1984 Pl. 5, figs 18-19

Coccolith indet. cf. *Hayella* sp.

Pl. 5, figs 27-28. **Description:** High, circular coccolith with relatively bright XPL image and strongly inclined elements. **Occurrence:** Zone NP13, Site 1407.

Coccolith indet. cf. *Scyphosphaera* sp.

Pl. 5, figs 29-31. **Description:** Very high nannofossil with gently tapering, narrow walls, seen in side view. **Occurrence:** Zone NP13, Site 1407.

Coccolith indet. cf. *Stauroolithites* sp.

Pl. 5, figs 32-33. **Description:** Small coccolith with high, narrow rim and axial cross. **Occurrence:** Zone NP22, Site 1411.

Mesozoic muralith lineages

Order EIFFELLITHALES Rood *et al.*, 1971

Family CHIASTOZYGACEAE Rood *et al.*, 1973

Jakubowskia leoniae Varol, 1989 Pl. 5, figs 34-35

Neocrepidolithus grandiculus Bown, 2005 Pl. 5, figs 36-37

Family GONIOLITHACEAE Deflandre, 1957

Goniolithus fluckigeri Deflandre, 1957 Pl. 5, figs 38-39

Cenozoic muraliths

Order ZYGODISCALES Young & Bown, 1997

Family HELICOSPHAERACEAE Black, 1971

Helicosphaera bramlettei (Müller, 1970) Jafar & Martini, 1975 Pl. 5, fig. 40; Pl. 14, fig. 16

Helicosphaera clarissima Bown, 2005 Pl. 5, fig. 41

Helicosphaera compacta Bramlette & Wilcoxon, 1967 Pl. 5, fig. 42; Pl. 14, fig. 19

Helicosphaera lophota (Bramlette & Sullivan, 1961) Locker, 1973 Pl. 5, fig. 43

Helicosphaera papillata Bukry & Bramlette, 1969 Pl. 5, fig. 44; Pl. 14, figs 17-18

Helicosphaera prolixa sp. nov.

Pl. 5, fig. 47-51. **Derivation of name:** From *prolixus*, meaning 'wide', referring to the broad overall shape of this species. **Diagnosis:** Large, broadly elliptical *Helicosphaera* with narrow

central area spanned by an oblique, disjunct, broad bar. The coccolith is relatively birefringent across the width of the rim. **Differentiation:** Distinguished from other *Helicosphaera* by the broadly elliptical outline and high birefringence image in XPL. **Dimensions:** Holotype L = 10.9 μm (Paratype L = 12.2 μm). **Holotype:** Pl. 5, fig. 47. **Paratype:** Pl. 5, fig. 49. **Type locality:** IODP Hole U1410A, NW Atlantic Ocean. **Type level:** Middle Eocene, Sample U1410A-14H-7, 82cm (Zone NP16). **Occurrence:** Zone NP16; IODP Site U1410.

Helicosphaera reticulata Bramlette & Wilcoxon, 1967 Pl. 5, fig. 45

Helicosphaera seminulum Bramlette & Sullivan, 1961 Pl. 14, fig. 15

Helicosphaera wilcoxonii (Gartner, 1971) Jafar & Martini, 1975 Pl. 5, fig. 46; Pl. 14, fig. 14

Family **PONTOSPHAERACEAE** Lemmermann, 1908

Pontosphaera alta Roth, 1970 Pl. 6, fig. 11

Pontosphaera clinosulcata Bown, 2005 Pl. 6, fig. 12

Pontosphaera enormis (Locker, 1967) Perch-Nielsen, 1984 Pl. 6, fig. 13

Pontosphaera exilis (Bramlette & Sullivan, 1961) Romein, 1979 Pl. 6, fig. 14

Pontosphaera formosa (Bukry & Bramlette, 1968) Romein, 1979 Pl. 6, figs 23-24

Pontosphaera latoculata (Bukry & Percival, 1971) Perch-Nielsen, 1984 Pl. 6, figs 15-16

Pontosphaera multipora (Kamptner, 1948 ex Deflandre, 1954) Roth, 1970 Pl. 6, fig. 25

Pontosphaera obliquipons (Deflandre in Deflandre & Fert 1954) Romein 1979 Pl. 6, fig. 22

Pontosphaera pulchra (Deflandre in Deflandre & Fert, 1954) Romein, 1979 Pl. 6, fig. 26; Pl. 14, fig. 20

Pontosphaera brinkhuisii sp. nov.

Pl. 6, fig. 1-4. **Derivation of name:** Named after Dan Brinkhuis (Science Media NL, The Netherlands), Exp. 342 videographer and film maker. **Diagnosis:** Very large, elliptical pontosphaerid with broad, high rim and narrow, apparently vacant central area. **Remarks:** Possibly the taxon that Bralower and Mutterlose (1995) call *Reticulofenestra "grandis"* with a reported range of Zones NP15-16. **Differentiation:** Distinguished from other *Pontosphaera* by larger size, thick rim cycles and vacant central area. **Dimensions:** Holotype L = 21.2 μm (Paratype L = 17.1 μm). **Holotype:** Pl. 6, fig. 1. **Paratype:** Pl. 6, fig. 3. **Type locality:** IODP Hole U1409A, NW Atlantic Ocean. **Type level:** Middle Eocene, Sample U1409A-7H-CC (Subzone NP15b). **Occurrence:** Subzone NP15b-16; IODP Sites U1408, U1409

Pontosphaera hollisii sp. nov.

Pl. 6, fig. 9-10. **Derivation of name:** Named after Chris Hollis (GNS Science, New Zealand), Exp. 342 shipboard scientist, micropalaeontologist and palaeoceanographer. **Diagnosis:** Very large, broadly elliptical pontosphaerid with broad, low rim and narrow to closed central area. The rim is pale grey in cross-polarised light. **Differentiation:** Distinguished from other *Pontosphaera* by larger size, broad rim cycle and low birefringence in cross-polarised light. **Dimensions:** Holotype L = 18.1 μm (Paratype L = 18.3 μm). **Holotype:** Pl. 6, fig. 9. **Paratype:** Pl. 6, figs 10. **Type locality:** IODP Hole U1409A, NW Atlantic Ocean. **Type level:** Middle Eocene, Sample U1409A-7H-CC (Subzone NP15b). **Occurrence:** Subzone NP15b-c; IODP Site U1409.

Pontosphaera romansii sp. nov.

Pl. 6, fig. 17-21. **Derivation of name:** Named after Brian Romans (Virginia Polytechnic Institute and State University, USA), Exp. 342 shipboard scientist, sedimentologist and palaeoceanographer. **Diagnosis:** Large, narrowly elliptical, lens-shaped pontosphaerid with high rim and apparently vacant central area. **Differentiation:** Distinguished from other pontosphaerids by the high, lens-shaped rim. **Dimensions:** Holotype L = 10.5 μm (Paratype L = 11.9 μm). **Holotype:** Pl. 6, fig. 17. **Paratype:** Pl. 6, fig. 21. **Type locality:** IODP Hole U1409A, NW Atlantic Ocean. **Type level:** Middle Eocene, Sample U1409A-8H-CC (Subzone NP15b). **Occurrence:** Subzone NP15b; IODP Site U1409.

Pontosphaera wilsonii sp. nov.

Pl. 6, fig. 5-8. **Derivation of name:** Named after Paul Wilson (University of Southampton, UK), Exp. 342 co-chief scientist and palaeoceanographer. **Diagnosis:** Elliptical pontosphaerid with central area plate crossed by prominent oblique ridges that are bright in cross-polarised light. **Differentiation:** Distinguished from other *Pontosphaera* by the distinctive oblique ridges than run across the coccolith. **Dimensions:** Holotype L = 6.7 μm (Paratype L = 7.4 μm). **Holotype:** Pl. 6, fig. 6. **Paratype:** Pl. 6, fig. 8. **Type locality:** IODP Hole U1410A, NW Atlantic Ocean. **Type level:** Middle Eocene, Sample U1410A-17X-1, 75 cm (Subzone NP15c). **Occurrence:** Subzone NP15b-16; IODP Sites U1408, U1409, U1410.

Pontosphaera zigzag (Roth & Hay, 1967 in Hay et al. 1967) comb. nov.

Pl. 6, figs 27-29 **Basionym:** *Transveropontis zigzag* Roth & Hay, 1967 in Hay et al. 1967, p. 450, Plate 7, fig. 4. *Transactions of the Gulf Coast Association of Geological Societies*, **17**, 428-480. **Description:** Small *Pontosphaera* with oblique bar usually with a distinct kink and perforate. **Remarks:** Reported as ranging from the middle Eocene (e.g. Self-Trail, 2011) to Oligocene but is often most conspicuous across the Eocene/Oligocene transition. **Occurrence:** Zone NP15c-22; IODP Site U1498, 1410 and 1411. NP14-16 (Self-Trail, 2011).

Scyphosphaera apsteinii Lohmann, 1902 Pl. 6, fig. 38-40; Pl. 12, fig. 9; Pl. 14, fig. 21

Scyphosphaera columella Stradner, 1969 Pl. 6, fig. 36

Scyphosphaera expansa Bukry & Percival, 1971 Pl. 6, fig. 37; Pl. 14, fig. 22

Scyphosphaera interstincta sp. nov.

Pl. 6, fig. 30-35. **Derivation of name:** From *interstinctus*, meaning 'spotted', referring to the appearance of the wall of this species. **Diagnosis:** Elongate-barrel shaped *Scyphosphaera* with distinct wall ornament of large pits or pores. The coccolith wall tapers gently both proximally and distally, and the inner cycle thickens at the distal opening. **Differentiation:** Distinguished from other *Scyphosphaera* by the wall ornament and inner cycle thickening at the distal opening. **Dimensions:** Holotype L/W = 7.7 μm ; H = 14.3 μm (Paratype L/W = 8.3 μm ; H = 14.3 μm). Holotype L/W = 6.1 μm ; H = 11.3 μm **Holotype:** Pl. 6, fig. 30. **Paratype:** Pl. 6, fig. 34. **Type locality:** IODP Hole U1408A, NW Atlantic Ocean. **Type level:** Upper Eocene, Sample U1408A-14H-5, 63cm (Zone NP16). **Occurrence:** Zone NP15b-16; IODP Sites U1408 and 1409.

Family **ZYGODISCAEAE** Hay & Mohler, 1967

Lophodolithus mochlophorus Deflandre in Deflandre & Fert, 1954 Pl. 8, figs 11-14

Lophodolithus rotundus Bukry & Percival 1971 Pl. 8, figs 15-16

***Neococcolithes-Nannotetrina* Group**

Pl. 7; Fig. 3. **Description:** Distinctive and unusual coccoliths/nannoliths ranging from simple muraliths (*Isthmolithus*, *Neococcolithes*), through modified-coccoliths with very high and ragged rims (*Chiphragmalithus*), to cruciform and stellate nannoliths, with relict or lost rims (*Nannotetrina*). All share a common crystallographic orientation with crystal units in near-extinction in cross-polarized light and most are characterised by the presence of diagonally-

orientated crossbars. In *Chiphragmolithus* the rim is elevated and often irregular in outline due to lateral outgrowths. In *Nannotetrina* the coccolith rim is lost or relict and the modified crossbars form the majority of the lith. Throughout the group the coccolith rims or nannoliths are high and often seen in side view (Pl. 7, figs 45-50). **Included genera:** *Chiphragmalithus*, *Isthmolithus*, *Nannotetrina*, *Neococcolithes*. **Occurrence:** Lower Paleocene-Lower Oligocene (Zones NP5?-NP22).

Genus *Chiphragmalithus* Bramlette and Sullivan, 1961

Chiphragmalithus acanthodes Bramlette and Sullivan, 1961

Pl. 7, figs 4-12. **Description:** Elliptical, high rim with lateral projections and central area spanned by diagonal crossbars. The crossbars are high and extend across the rim to the coccolith edge. **Remarks:** Occurs with a number of other unusual coccoliths (e.g. *N. plana*, *N. ruda*) close to the first appearance of the *Nannotetrina* genus (see discussion above). **Occurrence:** Zone NP14a-b; IODP Sites U1408 and 1409.

Chiphragmalithus calathus Bramlette & Sullivan, 1961

Pl. 7, figs 13-15. **Remarks:** Circular, subcircular or slightly quadrate with simple, high rim and diagonal crossbars. **Occurrence:** Zone NP14; IODP Sites U1408 and 1409.

Genus *Isthmolithus* Deflandre in Deflandre & Fert, 1954

Isthmolithus recurvus Deflandre in Deflandre and Fert, 1954 Fig. 3

Genus *Nannotetrina* Achuthan and Stradner, 1969

Nannotetrina alata (Martini, 1960) Haq and Lohmann, 1976 Pl. 12, fig. 11

Nannotetrina cristata (Martini, 1958) Perch-Nielsen, 1971 Pl. 7, figs 31-43, 50

Remarks: We use *N. cristata* here for an array of medium- to large-sized, three-dimensional nannoliths that are broadly cross-shaped with arms that widen towards their ends and with inter-arm fill. They are frequently seen in side view, where they resemble side views of *Chiphragmolithus* (Pl. 7, fig. 50). A small number of specimens observed in Subzone NP14b retain structures that appear to resemble small, square-shaped coccolith rims and central area bars (Pl. 7, figs 37-43).

Nannotetrina fulgens (Stradner in Martini & Stradner, 1960) Achuthan & Stradner, 1969 Pl. 12, fig. 12

Nannotetrina spinosa (Stradner in Martini & Stradner, 1960) Bukry, 1973 Pl. 7, fig. 44

Nannotetrina pappii (Stradner, 1959) Perch-Nielsen, 1971 Fig. 3

Nannotetrina plana sp. nov.

Pl. 7, figs 21-30 **Derivation of name:** From *planus*, meaning 'flat', referring to the relatively flat morphology of this species. **Diagnosis:** Subcircular to broadly elliptical form comprising a low basal disc crossed by broad, raised, crossbars. The constituent elements are in near-extinction in XPL. **Differentiation:** Distinguished from *Nannotetrina cristata* by rounder outline and relatively broader crossbars/ridges that do not thicken and twist at their ends. **Dimensions:** Holotype L = 9.0 μm (Paratype L = 9.3 μm). **Holotype:** Pl. 10, fig. 21. **Paratype:** Pl. 10, fig. 25. **Type locality:** IODP Hole U1409A, NW Atlantic Ocean. **Type level:** Middle Eocene, Sample U1409A-12H-4, 43cm (Subzone NP14b). **Occurrence:** Subzone NP14b; Sites U1408 and 1409.

Nannotetrina ruda sp. nov.

Pl. 7, figs 16-20. **Derivation of name:** From *ruda*, meaning 'rough lump', referring to the coarse and blocky appearance of this species. **Diagnosis:** Subcircular to broadly elliptical form comprising a rim and high, broad and blocky crossbars. The constituent elements are in near-extinction in XPL. **Differentiation:** Most similar to *Nannotetrina plana* sp. nov. but blockier in overall form and the crossbars are broader and higher. **Dimensions:** Holotype L = 11.2 μm (Paratype L = 9.8 μm). **Holotype:** Pl. 10, fig. 17. **Paratype:** Pl. 10, fig. 18. **Type locality:** IODP Hole U1409A, NW Atlantic Ocean. **Type level:** Middle Eocene, Sample U1409A-12H-4, 43cm (Subzone NP14b). **Occurrence:** Zone NP14b; IODP Site 1409.

Genus *Neococcolithes* Sujkowski, 1931

Neococcolithes dubius (Deflandre in Deflandre and Fert, 1954) Black, 1967 Pl. 7, fig. 1; Pl. 14, fig. 23

Neococcolithes protenus (Bramlette and Sullivan, 1961) Black, 1967

Pl. 7, figs 2-3, 45. **Remarks:** Elliptical, simple rim with diagonal crossbars.

Neococcolithes purus sp. nov.

Pl. 8, figs 8-10. **Derivation of name:** From *purus*, meaning 'plain', referring to the apparently vacant central area of this species. **Diagnosis:** Narrowly-elliptical muralith coccolith with narrow, low birefringence, unicyclic rim image and relatively wide, apparently vacant, central area. **Remarks:** To date, its distribution is the same as that of *Neococcolithes radiatus* sp. nov. **Differentiation:** Distinguished from other species of *Neococcolithes* by the vacant central area. Similar in overall form to *Jakubowskia leoniae* Varol, 1989 but it is smaller, has a narrower, low birefringence rim and a different stratigraphic range. **Dimensions:** Holotype L = 6.8 μm (Paratype L = 5.7 μm). **Holotype:** Pl. 8, fig. 8. **Paratype:** Pl. 8, fig. 10. **Type locality:** IODP Hole U1410A, NW Atlantic Ocean. **Type level:** Middle Eocene, Sample U1410A-7H-CC (Zone NP17). **Occurrence:** Zone NP17; IODP Sites 1408, 1410.

Neococcolithes radiatus sp. nov.

Pl. 8, figs 1-7. **Derivation of name:** From *radiatus*, meaning 'with rays', referring to the grill in the central area of this species. **Diagnosis:** Narrowly-elliptical muralith coccolith with low birefringence, unicyclic rim image and central area with numerous (around 18-22) radiating bars. **Description:** The rim shows relatively low birefringence in XPL as do the central area bars. Some specimens have outlines approaching rhomboidal. **Remarks:** The rhomboidal outline and stratigraphic position close to the extinction of *Neococcolithes dubius* and first appearance of *Isthmolithus recurvus* suggest that this may be a transitional species between the two genera. **Differentiation:** Distinguished from most other species of *Neococcolithes*, which have diagonal crossbars, by the more numerous central area bars. **Dimensions:** Holotype L = 7.6 μm (Paratype L = 6.4 μm). **Holotype:** Pl. 8, fig. 1. **Paratype:** Pl. 8, fig. 5. **Type locality:** IODP Hole U1410A, NW Atlantic Ocean. **Type level:** Middle Eocene, Sample U1410A-7H-CC (Zone NP17). **Occurrence:** Zone NP17; IODP Site 1410.

Family **RHABDOSPHAERACEAE** Haeckel, 1894

Genus *Blackites* Hay & Towe, 1962

Blackites bases

Pl. 8, figs 17-39. **Remarks:** In well preserved material *Blackites* bases can be common components of nannofossil assemblages, albeit inconspicuous because of their low birefringence images in XPL. They represent both the disarticulated bases of spinose forms, together with non-spinose coccoliths, such as *B. amplus*, *B. furvus*. Small *Blackites* bases (Pl.

8, figs 22-23) are common through the middle to late Eocene of the Exp. 342 sites, and are most likely the disarticulated bases of the common species *B. spinosus* and *B. tenuis*.

Blackites amplus Roth & Hay, 1967 Pl. 8, figs 17-21

Blackites creber (Deflandre in Deflandre & Fert, 1954) Sherwood, 1974 Pl. 9, fig. 9

Blackites dupuisii (Steurbaut, 1990) Bown, 2005 Pl. 8, figs 53-55

Blackites furvus Bown & Dunkley Jones, 2006 Pl. 8, figs 24-28

Blackites gladius (Locker, 1967) Varol, 1989 Pl. 9, figs 5-6; Pl. 15, fig. 3

Blackites globosus Bown, 2005 Pl. 8, figs 56-58

Blackites inflatus (Bramlette & Sullivan, 1961) Kapellos & Schaub, 1973 Pl. 9, figs 10, 30

Blackites kilwaensis Bown, 2005 Pl. 9, fig. 12

Blackites ornatus Bown & Dunkley Jones, 2006 Pl. 9, fig. 13

Blackites perlongus (Deflandre, 1952) Shafik, 1981 Pl. 9, figs 22-23

Blackites piriformis (Pavsic in Khan et al., 1975) Aubry, 1999 Pl. 9, fig. 11

Blackites pseudomorionum (Locker 1967) Aubry 1999 Pl. 8, fig. 46

Blackites cf. *B. pseudomorionum* (Locker 1967) Aubry 1999 Pl. 8, figs 44-45

Blackites rotundus Bown, 2005 Pl. 9, figs 7-8

Blackites spinosus (Deflandre & Fert, 1954) Hay & Towe, 1962 Pl. 9, figs 31-32; Pl. 15, fig.

4

Blackites cf. *B. spinosus* (Deflandre & Fert, 1954) Hay & Towe, 1962 Pl. 9, fig. 21

Blackites stilus Bown, 2005 Pl. 9, figs 24-25

Blackites tenuis (Bramlette & Sullivan 1961) Sherwood, 1974 Pl. 9, figs 33-34; Pl. 15, fig. 5

Blackites tortilis Bown & Dunkley Jones, 2006 Pl. 9, figs 16-20; Pl. 15, fig. 6

Blackites virgatus Bown, 2005 Pl. 9, figs 14-15

Blackites deflandrei (Perch-Nielsen 1968) Bown, 2005 var. 1

Pl. 8, figs 42, 43, 47; Pl. 15, figs 1-2. **Remarks:** *Blackites* with broad coccolith base and broad, thin-walled, variably tall, dome-like to bullet-shaped spine. The spine is ornamented and parallel-sided in its lower part before tapering to a point. In SEM the ornamentation is revealed to be perforations/windows. The species was originally defined and illustrated as having variable spine height but the complete type specimens have a height less than the coccolith rim width. Here we distinguish two informal varieties based on spine height: variety 1 with height < coccolith rim width and variety 2 with height > coccolith rim width.

Blackites deflandrei (Perch-Nielsen 1968) Bown, 2005 var. 2

Pl. 8, figs 48-52. **Remarks:** Like *B. deflandrei* var. 1 but with with spine height > coccolith rim width. **Occurrence:** Zone NP16-19/20; IODP Site U1410, 1411.

Blackites cf. *B. herculesii* (Stradner, 1969) Bybell & Self-Trail, 1997

Pl. 9, figs 35-39. **Remarks:** Tall, narrow, club-like, disarticulated *Blackites* spines that narrow towards both ends and which have a dark image in XPL. **Occurrence:** Zones 15b-17; Site U1409.

Blackites friedrichii sp. nov.

Pl. 8, figs 29-39. **Derivation of name:** Named after Oliver Friedrich (University of Heidelberg, Germany), Exp. 342 shipboard scientist, micropalaeontologist and palaeoceanographer. **Diagnosis:** *Blackites* with broad circular base and broad, low, thin-walled, globular spine with distinct image in XPL having a crenulate edge and strong extinction cross. Typically seen in plan view. **Differentiation:** Distinguished from most *Blackites* bases by its large diameter and from *B. amplus* by its distinctive, low, globular spine. **Dimensions:** Holotype L = 5.4 μm (Paratype L = 4.5 μm). **Holotype:** Pl. 7, fig. 33. **Paratype:** Pl. 7, fig. 30. **Type locality:** IODP Hole U1408C, NW Atlantic Ocean. **Type level:** Middle Eocene, Sample U1408C-10X-3, 63cm (Zone NP16). **Occurrence:** Zones NP16-17; IODP Site U1408, 1409, 1410.

Blackites sextonii sp. nov.

Pl. 9, figs 1-4. **Derivation of name:** Named after Phil Sexton (Open University, UK), Exp. 342 shipboard scientist, micropalaeontologist and palaeoceanographer. **Diagnosis:** *Blackites* with broad base, and very tall, broad, thin-walled spine. The broad spine is near-parallel sided or very gently tapering for most of its length before tapering sharply to a point. **Differentiation:** Distinguished from other *Blackites* by its broad, very tall spine. **Dimensions:** Holotype max coccolith base W = 5.9 μm ; spine L = 13.1 μm , spine W = 2.3 μm (Paratype spine L = 12.7 μm). **Holotype:** Pl. 8, fig. 1. **Paratype:** Pl. 8, figs 3, 4. **Type locality:** IODP Hole U1408C, NW Atlantic Ocean. **Type level:** Upper Eocene, Sample U1408C-7H-4, 93cm (Zone NP16). **Occurrence:** Zone NP16; IODP Site U1408.

Blackites subtilis sp. nov.

Pl. 9, figs 27-29. **Derivation of name:** From *subtilis*, meaning ‘slender’, referring to the very narrow form of this spine. **Diagnosis:** Very long, slender spine that is near-parallel-sided with a narrow axial canal. In XPL, the spine is dark when parallel with the polarising directions and bright at 45°. It is typically seen with no basal coccolith. **Differentiation:** Most likely a spine of the genus *Blackites*, but distinguished from other narrow-spined species, such as *B. perlongus* and *B. tenuis*, by its length, very narrow axial canal and lack of taper. **Dimensions:** Holotype spine L = 22.4 µm, spine W = 1.2 µm (Paratype minimum L = 16.1 µm, spine W = 1.2 µm). **Holotype:** Pl. 8, fig. 27. **Paratype:** Pl. 8, fig. 28. **Type locality:** IODP Hole U1407A, NW Atlantic Ocean. **Type level:** Upper Eocene, Sample U1407A-9H-6, 57cm (Subzone NP14b). **Occurrence:** Subzone NP14b-Zone NP16; IODP Sites U1407, U1408 and U1409.

Blackites inversus (Bukry & Bramlette, 1969) comb. nov.

Pl. 9, fig. 26. **Basionym:** *Triquetrorhabdulus inversus* Bukry & Bramlette, 1969, Some new and stratigraphically useful calcareous nannofossils of the Cenozoic. *Tulane Studies in Geology*, 7: p.142, pl. 1, figs 9-14. **Description:** Very long spinose forms that taper towards each end and which have undulating outline and narrow axial canal. In XPL they are dark at 0° and bright at 45°. **Remarks:** Previously placed in *Triquetrorhabdulus* by Bukry & Bramlette (1969) and *Pseudotriquetrorhabdulus* by Wise (in Wise & Constans, 1976), these spinose forms occur alongside other *Blackites* spines with similar LM image and crystallographic orientation, and they most likely represents a *Blackites* species that readily detaches from its coccolith base. It can occur abundantly and has a relatively restricted stratigraphic range in the middle Eocene (Zones NP14-15), with a particular acme interval in Zone NP14 (Backman, 1986). **Occurrence:** Zones NP14-15.

Rhabdosphaera gracilenta (Bown & Dunkley Jones, 2006) Dunkley Jones et al., 2009

Pl. 9, figs 40-44. **Remarks:** Transferred from *Blackites* to *Rhabdosphaera* by Dunkley Jones et al. (2009) but spelt *gracilentus*. Orthography corrected here.

Rhabdosphaera vitrea (Deflandre in Deflandre & Fert 1954) Bramlette & Sullivan, 1961 Pl. 9, figs 45-48

Order SYRACOSPHAERALES Hay, 1977 emend. Young et al., 2003

Family CALCIOSOLENIACEAE Kamptner, 1927

Calciosolenia alternans Bown & Dunkley Jones, 2006 Pl. 9, fig. 49

Family **SYRACOSPHAERACEAE** Lemmermann, 1908

Syracosphaera octiforma sp. nov.

Pl. 9, figs 51-54. **Derivation of name:** From *octi*, meaning 'eight', and '*forma*' meaning form, referring to the distinctive outline of this species. **Diagnosis:** Narrow rimmed coccolith with figure-of-eight outline (indentations on each side). In XPL the rim is relatively bright and there may be a spine in the central area, which is otherwise unclear. **Remarks:** We tentatively assign this species to *Syracosphaera* based on the rim image in XPL. **Differentiation:** Distinguished from most other coccoliths by its distinctive outline. **Dimensions:** Holotype L = 5.5 μm (Paratype L = 5.2 μm). **Holotype:** Pl. 9, fig. 53. **Paratype:** Pl. 9, fig. 51. **Type locality:** IODP Hole U1408A, NW Atlantic Ocean. **Type level:** Upper Eocene, Sample U1408A-4H-CC (Zone NP17). **Occurrence:** Zone NP16-17; IODP Sites U1408, 1410.

Syracosphaera tanzanensis Bown, 2005 Pl. 8, fig. 50

Murolith coccoliths *Incertae Sedis*

Pocillithus spinulifer Dunkley Jones et al., 2009 Pl. 15, figs 7-8

HOLOCOCOLITHS

Family **CALYPTROSPHAERACEAE** Boudreaux & Hay, 1967

Daktylethra punctulata Gartner in Gartner & Bukry, 1969 Pl. 10, figs 4-6

Daktylethra unitatis Bown & Dunkley Jones, 2006 Pl. 10, figs 1-3; Pl. 15, fig. 9

Holodiscolithus solidus (Deflandre in Deflandre & Fert, 1954) Roth, 1970 Pl. 10, figs 9-13;
Pl. 15, fig. 10

Lanternithus minutus Stradner, 1962 Pl. 10, figs 7-8; Pl. 15, fig. 11

Holodiscolithus agniniae sp. nov.

Pl. 10, figs 14-21. **Derivation of name:** Named after Claudia Agnini (University of Padua, Italy), Exp. 342 shipboard scientist, nannopaleontologist and biostratigrapher. **Remarks:** Flat, elliptical holococcolith formed from six crystallographic blocks divided by near-radial sutures. **Differentiation:** Similar to Cretaceous coccoliths of the genus *Calculites*, but this species is distinguished by being flat and having six similarly-sized crystallographic blocks. **Dimensions:**

Holotype L = 4.9 μm (Paratype L = 4.8 μm). **Holotype:** Pl. 9, fig. 17. **Paratype:** Pl. 9, fig. 14. **Type locality:** IODP Hole U1407A, NW Atlantic Ocean. **Type level:** Middle Eocene, Sample U1407A-9H-6, 58cm (Subzone NP14b). **Occurrence:** Subzone NP14b; IODP Site U1407.

Holodiscolithus liuii sp. nov.

Pl. 10, figs 22-26. **Derivation of name:** Named after Zhonghui Liu (Department of Earth Sciences, University of Hong Kong), Exp. 342 shipboard scientist, geochemist and palaeoceanographer. **Diagnosis:** Small, elliptical holococcolith with narrow rim and broad bar that almost fills the central area; the bar is dark at 0° and birefringent at 45°. **Differentiation:** Similar to *H. serus* but is more regular in outline and shows no perforations. **Dimensions:** Holotype L = 3.9 μm (Paratype L = 3.9 μm). **Holotype:** Pl. 9, fig. 25. **Paratype:** Pl. 9, fig. 22. **Type locality:** IODP Hole U1407A, NW Atlantic Ocean. **Type level:** Middle Eocene, Sample U1407A-9H-6, 57cm (Subzone NP14b). **Occurrence:** Subzone NP14b; IODP Site U1407.

Holodiscolithus lippertii sp. nov.

Pl. 10, figs 33-38. **Derivation of name:** Named after Peter Lippert (University of Utah, USA), Exp. 342 shipboard scientist, palaeomagnetist and palaeoceanographer. **Diagnosis:** Small, elliptical, moderately-birefringent holococcolith crossed by roughly diagonal extinction lines in XPL delineating four blocks, which are birefringent at 0° and dark at 45°. There are around 8-10 perforations across the blocks and raised axial ridges are visible in phase contrast. **Differentiation:** The perforations are smaller than *Holodiscolithus solidus* and less numerous than *Holodiscolithus macroporus*. **Dimensions:** Holotype L = 3.2 μm (Paratype L = 3.4 μm). **Holotype:** Pl. 9, fig. 36. **Paratype:** Pl. 9, fig. 33. **Type locality:** IODP Hole U1411B, NW Atlantic Ocean. **Type level:** Eocene/Oligocene transition, Sample U1411C-8H-6, 60cm (Zone NP21). **Occurrence:** Zone NP21; IODP Site U1411.

Holodiscolithus whitesideae sp. nov.

Pl. 10, figs 27-30. **Derivation of name:** Named after Jessica Whiteside (University of Southampton, UK), Exp. 342 shipboard scientist, geochemist and palaeoceanographer. **Diagnosis:** Small holococcolith seen in side view, with steep-sided base and short, narrow spine. All parts of the holococcolith show similar crystallographic orientation and it is moderately birefringent at 45°, and dark at 0°. A median septum appears to be present. **Differentiation:** **Dimensions:** Holotype L = 3.1 μm , H = 3.3 μm (Paratype L = 2.8 μm , H =

2.9 μm). **Holotype:** Pl. 9, fig. 28. **Paratype:** Pl. 9, fig. 29. **Type locality:** IODP Hole U1408C, NW Atlantic Ocean. **Type level:** Middle Eocene, Sample U1408C-10H-3, 63cm (Zone NP16). **Occurrence:** Zone NP16; IODP Site U1408.

Semihololithus pseudobiskayae sp. nov.

Pl. 10, figs 39-44. **Derivation of name:** From the Greek word *pseudes*, meaning ‘false’, and referring to its similarity to the older, Paleocene species *Semihololithus biskayae*. **Diagnosis:** Large, blocky coccolith seen in side view, with steep-walled rim and domed upper surface. **Differentiation:** Similar in overall shape to *Semihololithus biskayae* but has a more irregular appearance, lower birefringence image and blockier upper cover. **Dimensions:** Holotype L = 6.6 μm , H = 6.5 μm (Paratype L = 6.6 μm , H = 6.8 μm). **Holotype:** Pl. 9, fig. 43. **Paratype:** Pl. 9, fig. 41. **Type locality:** IODP Hole U1407A, NW Atlantic Ocean. **Type level:** Middle Eocene, Sample U1407A-9H-6, 57cm (Subzone NP14b). **Occurrence:** Subzone NP14b; IODP Sites U1407 and U1408.

Zygrhablithus bijugatus bijugatus (Deflandre in Deflandre & Fert, 1954) Deflandre, 1959 Pl. 10, figs 45-50; Pl. 15, fig. 12

Holococcolith sp. indet.

Pl. 10, figs 31-32. **Remarks:** Small, elliptical holococcolith with transverse bar, displaying a low birefringence image in XPL and high relief in PC. Occurrence: Middle Eocene, Subzone NP14b; Site 1407.

EXTINCT NANNOLITHS

Order DISCOASTERALES Hay, 1977 emend. Bown, 2010

Family DISCOASTERACEAE Tan, 1927

Discoaster barbadiensis Tan, 1927 Pl. 15, fig. 14

Discoaster distinctus Martini, 1958 Pl. 15, fig. 17

Discoaster martinii Stradner, 1959 Pl. 12, fig. 10

Discoaster nodifer (Bramlette & Riedel, 1954) Bukry, 1973 Pl. 15, figs 15, 18

Discoaster saipanensis Bramlette & Riedel, 1954 Pl. 15, fig. 13

Family SPHENOLITHACEAE Deflandre, 1952

***Sphenolithus furcatolithoides* Subgroup**

Pl. 11, figs 1-29. **Remarks:** Included within the *S. radians* group by Bown and Dunkley Jones (2012), these species are characterised by two (rarely more) bifurcating apical spines, bright at 0° and dark at 45°, extending from the upper quadrants. Species differentiation is based on the height and angle of spine bifurcation and size of the basal quadrants. In moderate to poor preservation the upper portion of these tall spines is usually lost, but when well preserved, as seen herein, the entire lith may be preserved, highlighting the extreme spine lengths (up to 25 µm; Pl. 11, fig. 25) and variations in upper spine morphology. Morphology within the group includes:

1. *S. kempii* – square base with three or four spines;
2. *S. cf. S. perpendicularis* – tapering base with narrow, high-angled lateral spines;
3. *S. perpendicularis* Shamrock, 2010 – square base with two spines that diverge by around 90°;
4. *S. furcatolithoides* – spines diverge just above the base and are near-parallel in the lower part;
5. *S. cuniculus* – forms with low basal quadrants ('feet') and ~90° bifurcations; and
6. *S. strigosus* – duocrystalline spines that bifurcate high-up on the spine.

In the slightly younger, and probably descendant, *S. predistentus* group, only the lower quadrants are clearly discernable in the basal column and the spines are bright at 45° and diverge in the uppermost part of the spine (e.g. *S. obtusus*, *S. runus*, *S. predistentus*).

Sphenolithus cuniculus Bown, 2005 Pl. 11, figs 19-20, 25

Sphenolithus furcatolithoides Locker 1967 Pl. 11, figs 15-18, 21-22, 26

Description: Typified by two apical spines that extend and diverge from the upper basal quadrants but that are near-parallel in the lower, normally preserved, part. When preservation is very good, the upper part of the spines are preserved and may be near-parallel or diverge from the long axis of the sphenolith by varying amounts. Variants include small, gracile forms with near-parallel bifurcations that bend to form higher degree (>90°) bifurcations high on the spine (Pl. 11, fig. 26), and forms with upper spines that converge (Pl. 11, fig. 22). Specimens at the base of the species range at Site U1410 appear most similar to *S. radians* (Pl. 11, figs 14-15).

Sphenolithus cf. *S. kempii* sensu Bown & Dunkley Jones, 2012 Pl. 11, figs 4-6

Sphenolithus perpendicularis Shamrock, 2010 Pl. 11, figs 9-13

Description: Sphenolith with two apical spines that diverge by $\sim 90^\circ$ (45° to the sphenolith long axis) just above the basal cycles. Restricted to Subzone NP15a according to Shamrock (2010). Informally identified as *Sphenolithus "spinatus"* by Bralower and Mutterlose (1995) and shown ranging from upper Subzone NP14b to Subzone NP15b. The *S. perpendicularis*-like forms seen in the Exp. 342 material have narrower spines but this may be due to overgrowth in the type material. Forms where the spines make a distinct angle with the upper basal quadrant are distinguished as *Sphenolithus* cf. *S. perpendicularis* herein. **Occurrence:** Subzone NP14b-15b. Sites 1407, 1408.

Sphenolithus cf. *S. perpendicularis* Shamrock, 2010 Pl. 11, figs 1-3

Description: Short, squat sphenoliths with a base formed from broad, gently-tapering lower quadrants and smaller upper quadrants. Two long, narrow, lateral spines emerge from the upper quadrants making an angle of around 160° (80° to the sphenolith long axis). **Differentiation:** The base is most similar to *S. moriformis* or *S. spiniger* but this species is distinguished from these by long lateral spines. The spines are most similar to *S. furcatolithoides* group sphenoliths, but are narrower and emerge from the base at a higher angle. **Occurrence:** Subzone NP14b-15b. Site 1408.

Sphenolithus strigosus Bown & Dunkley Jones 2006 Pl. 11, figs 23, 27-29; Pl. 15, fig. 22

***Sphenolithus predistentus* Group**

Pl. 11, figs 30-43. **Remarks:** These species are characterised by a base with two, low quadrants (or 'feet') and tapering duo- or monocrystalline spines with terminal bifurcations that may be very long. The spines are visible but dim at 0° and brightest when at 45° to the polarizing directions.

Sphenolithus obtusus Bukry 1971 Pl. 11, figs 36-38, 40-41; Pl. 15, fig. 21

Sphenolithus predistentus Bramlette & Wilcoxon 1967 Pl. 11, figs 42-43

Sphenolithus runus Bown & Dunkley Jones 2006 Pl. 11, figs 30-35

Remarks: Similar to *S. obtusus* but the spine is dark at 0° and does not appear duocrytalline at 45°.

Other sphenoliths

Sphenolithus moriformis (Brönnimann & Stradner, 1960) Bramlette & Wilcoxon, 1967 Pl. 15, fig. 19

Sphenolithus radians Deflandre in Grassé 1952 Pl. 15, fig. 16

Sphenolithus spiniger Bukry 1971 Pl. 15, fig. 20

Sphenolithus spines

Pl. 11, figs 24, 39, 44-45. **Remarks:** Several middle Eocene sphenoliths have very tall spines which when well preserved retain even longer, usually bifurcating, terminal spine ends (e.g. *S. cuniculus*, *S. furcatolithoides*, *S. obtusus*, *S. strigosus*). These spines may reach up to 32µm in length and in *S. furcatolithoides* they take on a variety of different shapes, with up to two inflection points. In a number of stratigraphic intervals narrow spine-like liths are common and may represent broken sphenolith spines. However, in some case these liths have triradiate form, which do not appear to have been sourced from sphenoliths (Pl. 11, figs 39, 45).

Incertae Sedis Nannoliths

Leesella procera Bown & Dunkley Jones, 2006 Pl. 11, figs 46-48

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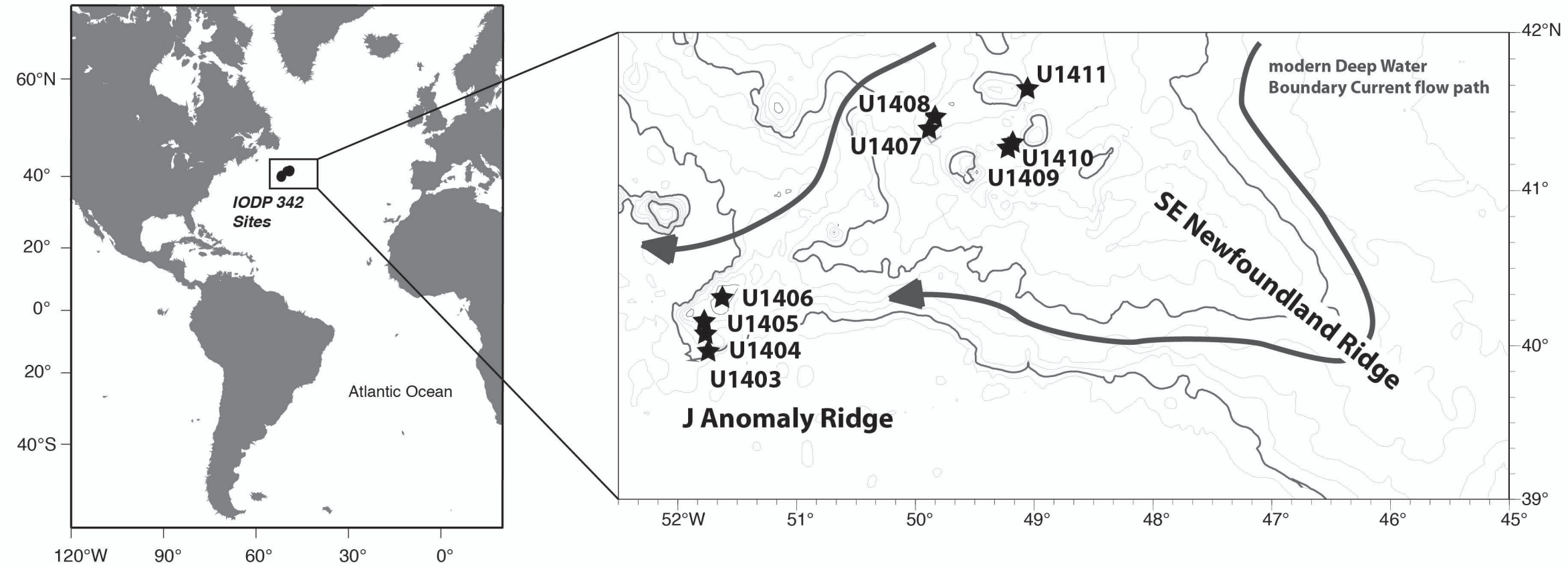
Figure Captions

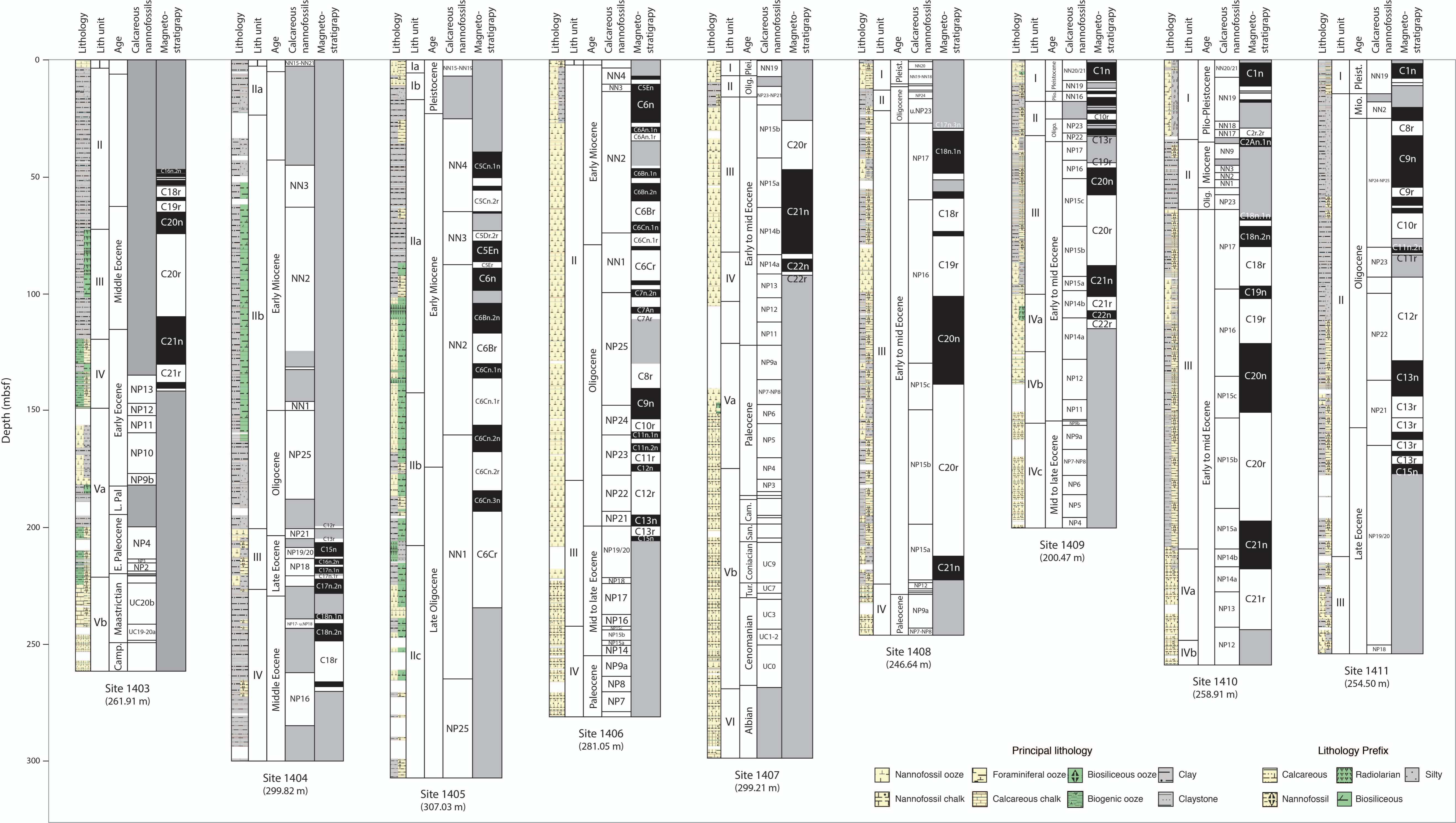
Figure 1. Location map of the sites drilled during IODP Expedition 342.

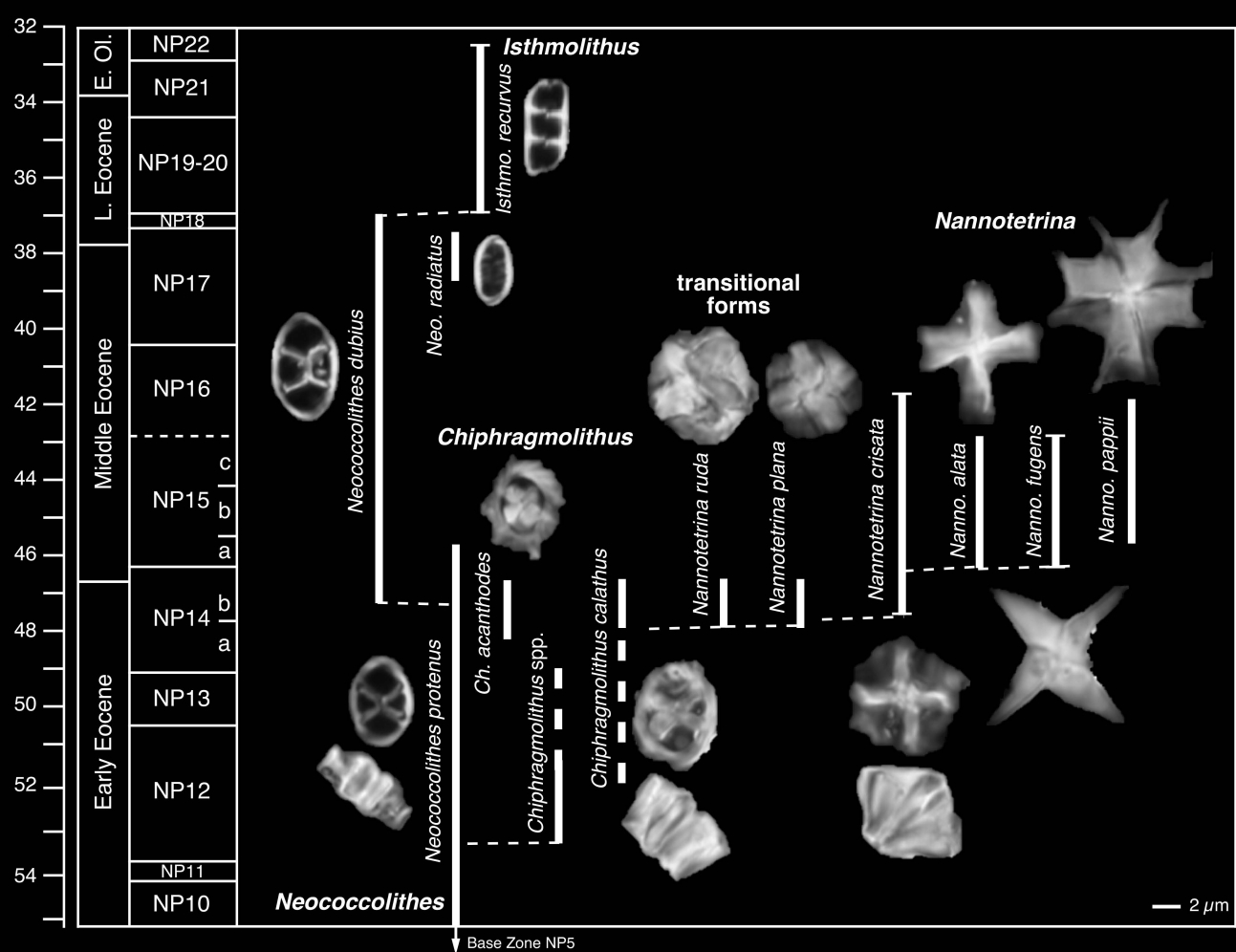
Figure 2. Summary of the stratigraphy recovered during IODP Expedition 342 (after Norris *et al.*, 2014).

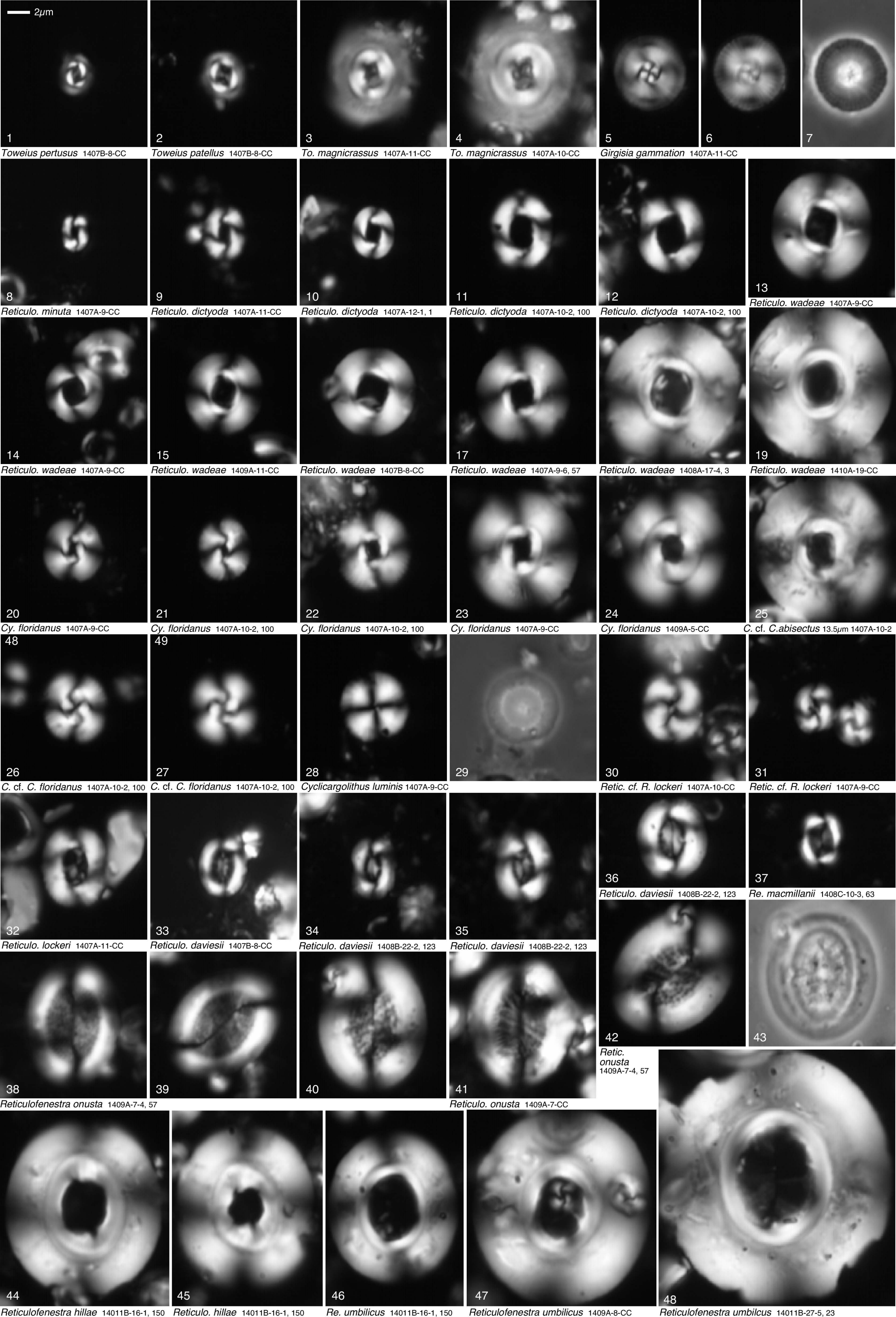
Figure 3. Stratigraphic distribution and possible phylogentic relationships within *Nannotetrina* and related taxa. The timescale is from Norris *et al.* (2014). Dotted vertical lines are uncertain stratigraphic ranges, horizontal bars indicate well constrained range base or top.

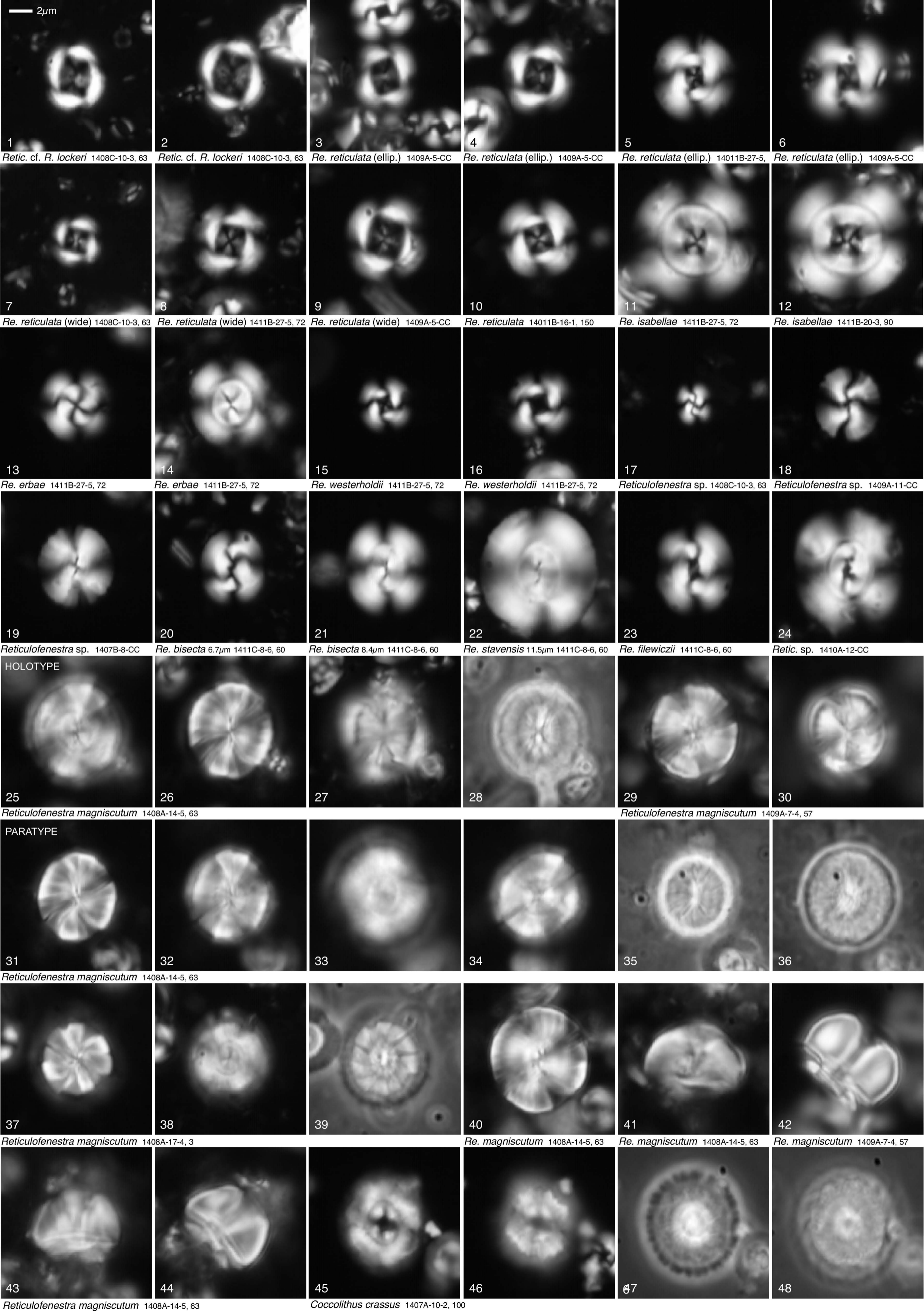
Plates 1 – 15.

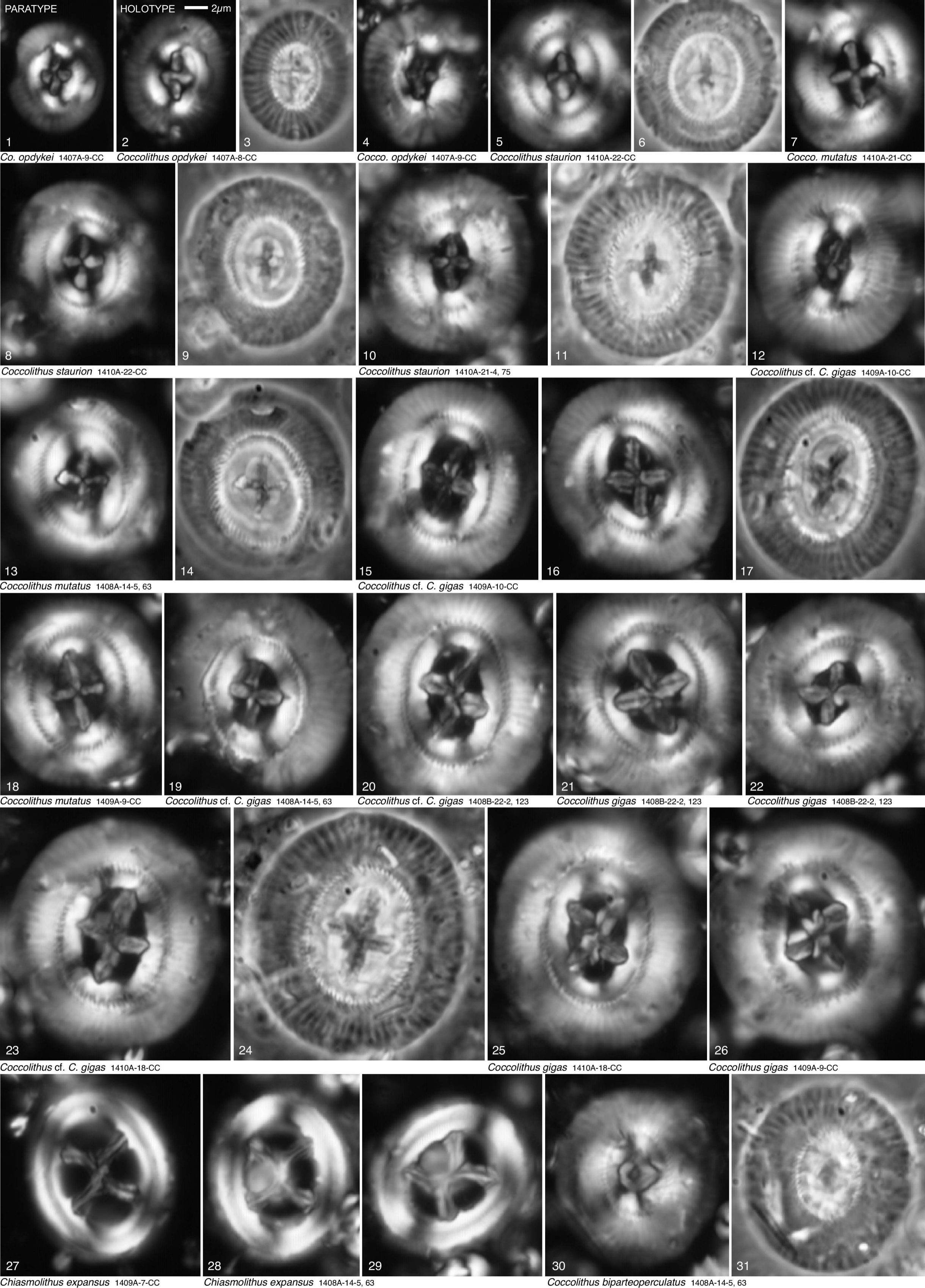












PARATYPE
1
Co. opdykei 1407A-9-CC

HOLOTYPE 2µm
2
Coccolithus opdykei 1407A-8-CC

3
Cocco. opdykei 1407A-9-CC

4
Coccolithus staurion 1410A-22-CC

5
Cocco. mutatus 1410A-21-CC

6

7

8
Coccolithus staurion 1410A-22-CC

9

10
Coccolithus staurion 1410A-21-4, 75

11

12
Coccolithus cf. C. gigas 1409A-10-CC

13
Coccolithus mutatus 1408A-14-5, 63

14

15
Coccolithus cf. C. gigas 1409A-10-CC

16

17

18
Coccolithus mutatus 1409A-9-CC

19
Coccolithus cf. C. gigas 1408A-14-5, 63

20
Coccolithus cf. C. gigas 1408B-22-2, 123

21
Coccolithus gigas 1408B-22-2, 123

22
Coccolithus gigas 1408B-22-2, 123

23
Coccolithus cf. C. gigas 1410A-18-CC

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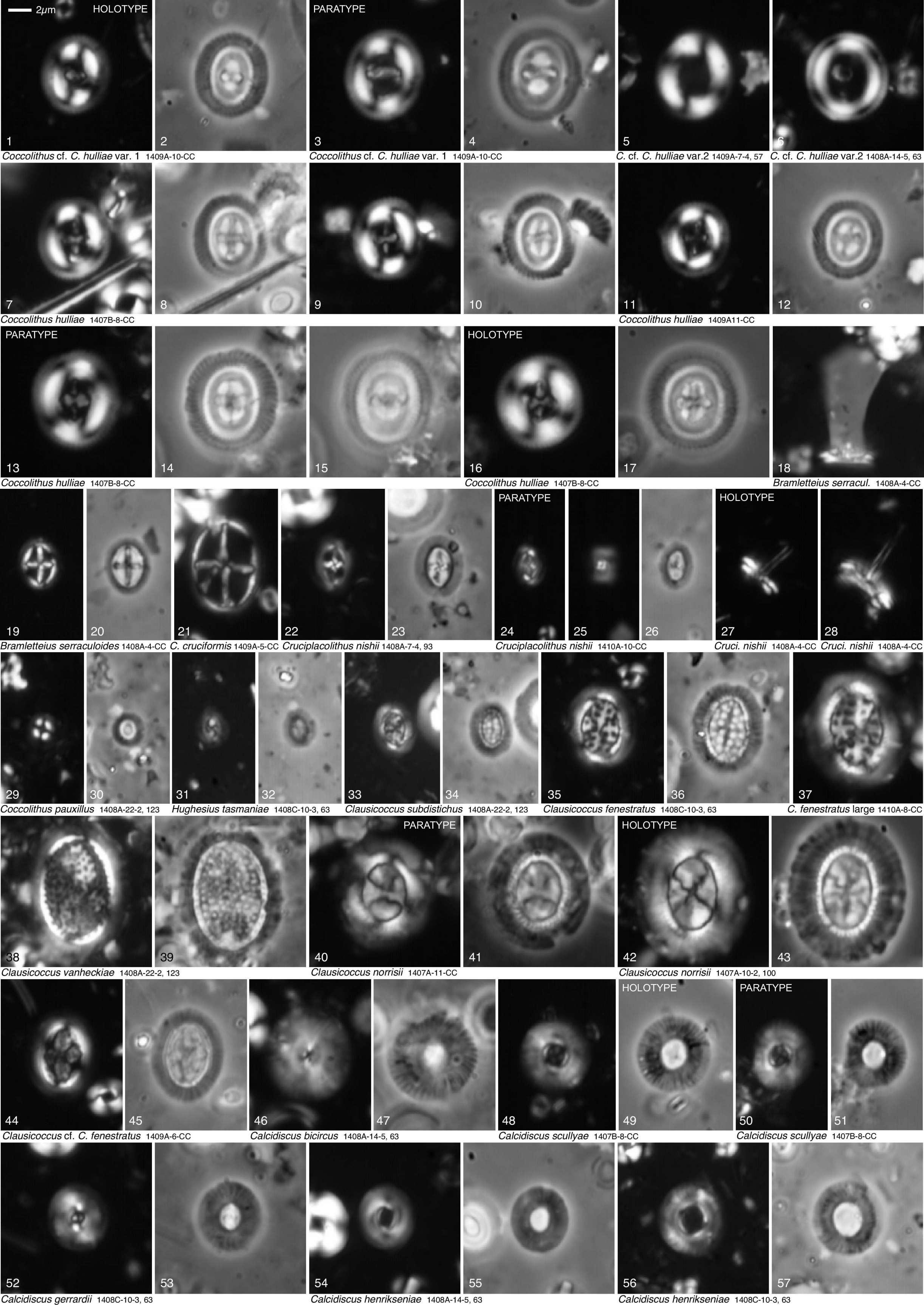
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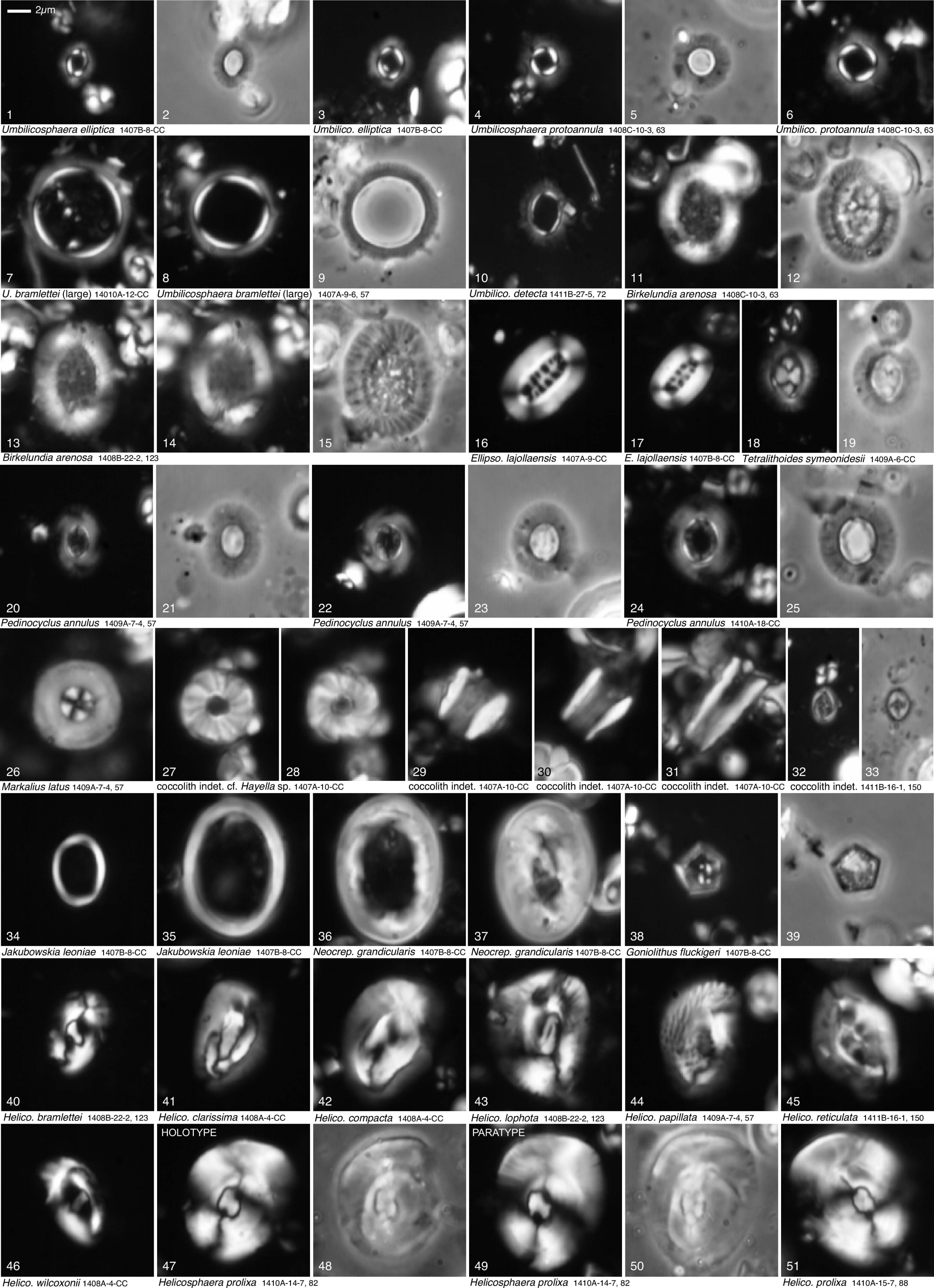
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Chiasmolithus expansus 1408A-14-5, 63

29

30
Coccolithus biparteoperculatus 1408A-14-5, 63

31





2µm

1 *Umbilicosphaera elliptica* 1407B-8-CC 2 *Umbilico. elliptica* 1407B-8-CC 3 *Umbilicosphaera protoannula* 1408C-10-3, 63 4 *Umbilico. protoannula* 1408C-10-3, 63 5 *Umbilico. protoannula* 1408C-10-3, 63 6 *Umbilico. protoannula* 1408C-10-3, 63

7 *U. bramlettei* (large) 14010A-12-CC 8 *Umbilicosphaera bramlettei* (large) 1407A-9-6, 57 9 *Umbilico. detecta* 1411B-27-5, 72 10 *Birkelundia arenosa* 1408C-10-3, 63 11 *Birkelundia arenosa* 1408C-10-3, 63 12 *Birkelundia arenosa* 1408C-10-3, 63

13 *Birkelundia arenosa* 1408B-22-2, 123 14 *Birkelundia arenosa* 1408B-22-2, 123 15 *Birkelundia arenosa* 1408B-22-2, 123 16 *Ellipso. lajollaensis* 1407A-9-CC 17 *E. lajollaensis* 1407B-8-CC 18 *Tetralithoides symeonidesii* 1409A-6-CC 19 *Tetralithoides symeonidesii* 1409A-6-CC

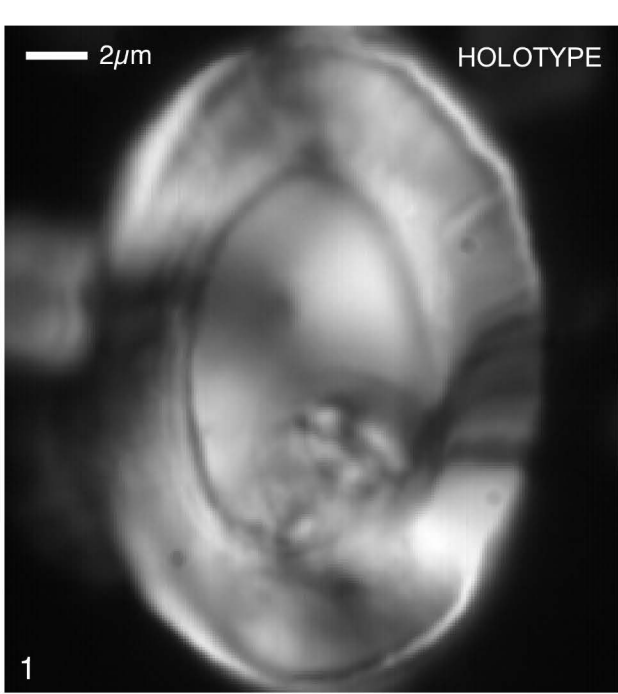
20 *Pedinocyclus annulus* 1409A-7-4, 57 21 *Pedinocyclus annulus* 1409A-7-4, 57 22 *Pedinocyclus annulus* 1409A-7-4, 57 23 *Pedinocyclus annulus* 1409A-7-4, 57 24 *Pedinocyclus annulus* 1410A-18-CC 25 *Pedinocyclus annulus* 1410A-18-CC

26 *Markalius latus* 1409A-7-4, 57 27 coccolith indet. cf. *Hayella* sp. 1407A-10-CC 28 coccolith indet. 1407A-10-CC 29 coccolith indet. 1407A-10-CC 30 coccolith indet. 1407A-10-CC 31 coccolith indet. 1407A-10-CC 32 coccolith indet. 1411B-16-1, 150 33 coccolith indet. 1411B-16-1, 150

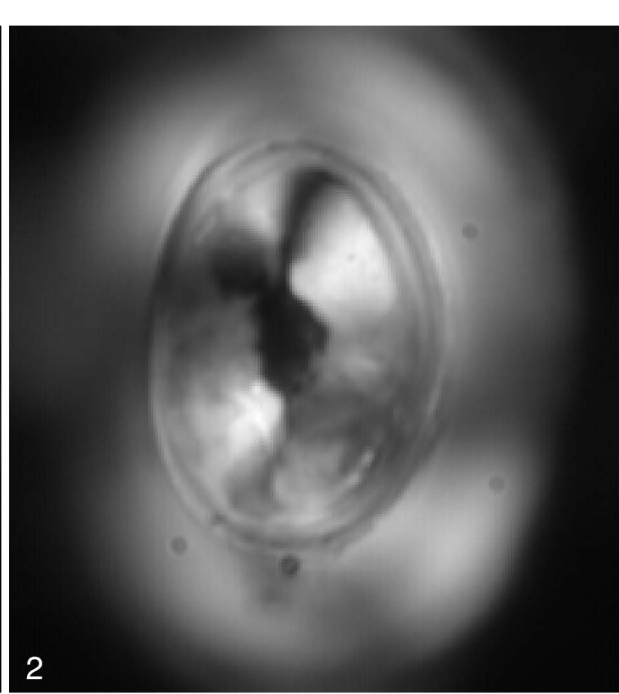
34 *Jakubowskia leoniae* 1407B-8-CC 35 *Jakubowskia leoniae* 1407B-8-CC 36 *Neocreponia grandicularis* 1407B-8-CC 37 *Neocreponia grandicularis* 1407B-8-CC 38 *Goniolithus fluckigeri* 1407B-8-CC 39 *Goniolithus fluckigeri* 1407B-8-CC

40 *Helico. bramlettei* 1408B-22-2, 123 41 *Helico. clarissima* 1408A-4-CC 42 *Helico. compacta* 1408A-4-CC 43 *Helico. lophota* 1408B-22-2, 123 44 *Helico. papillata* 1409A-7-4, 57 45 *Helico. reticulata* 1411B-16-1, 150

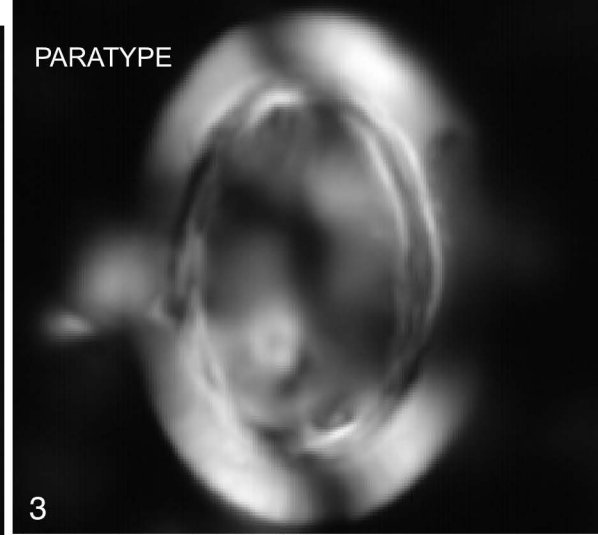
46 *Helico. wilcoxonii* 1408A-4-CC 47 HOLOTYPE *Helicosphaera prolixa* 1410A-14-7, 82 48 *Helicosphaera prolixa* 1410A-14-7, 82 49 PARATYPE *Helicosphaera prolixa* 1410A-14-7, 82 50 *Helicosphaera prolixa* 1410A-14-7, 82 51 *Helico. prolixa* 1410A-15-7, 88



HOLOTYPE

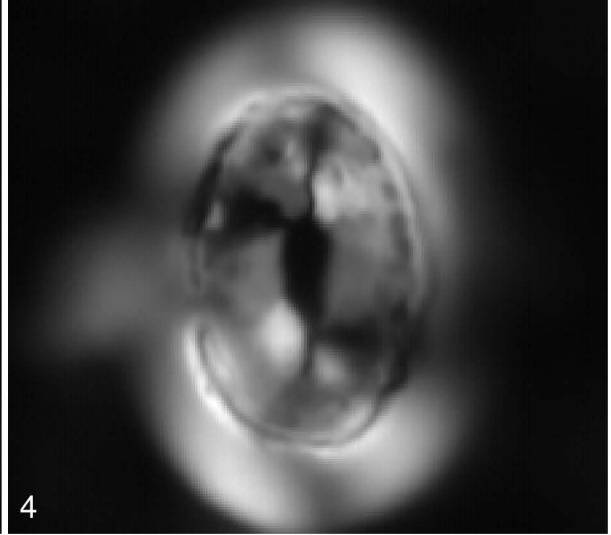


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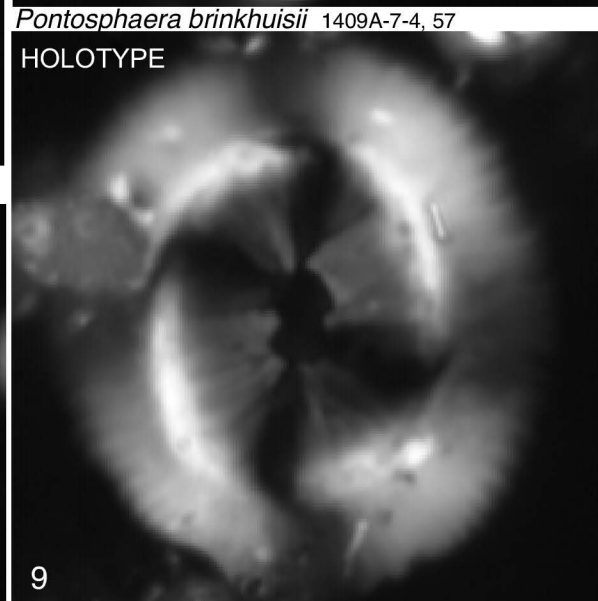


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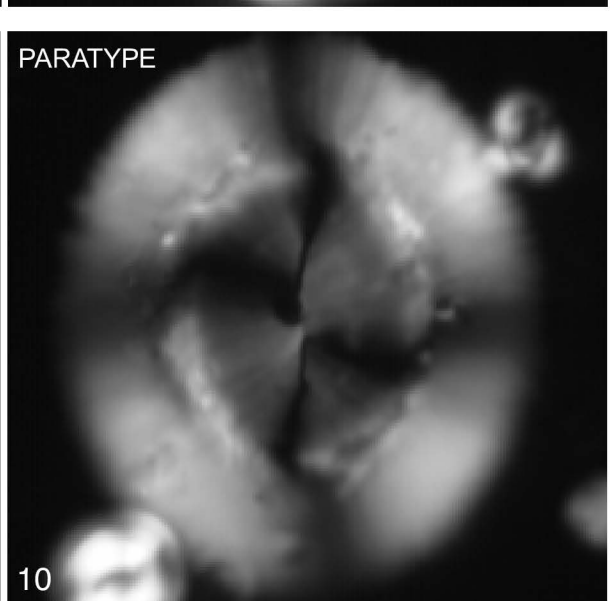


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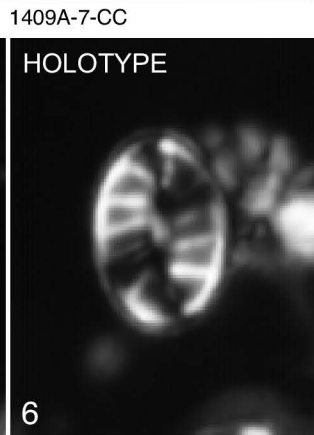
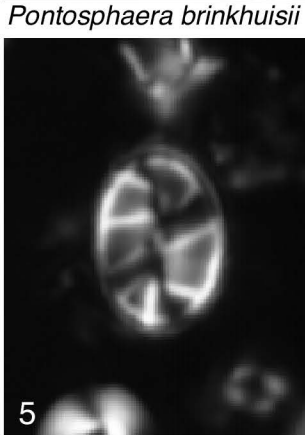
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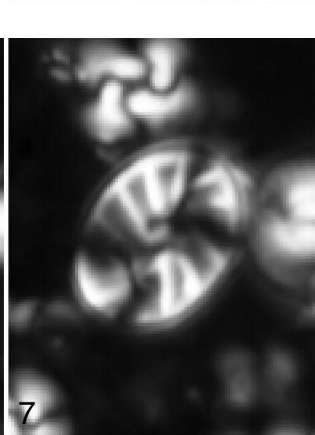
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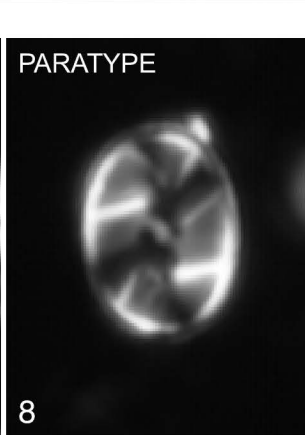


HOLOTYPE

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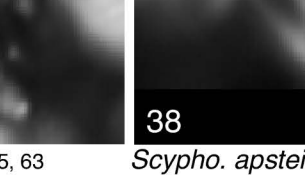
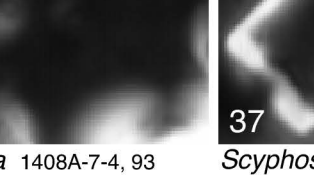
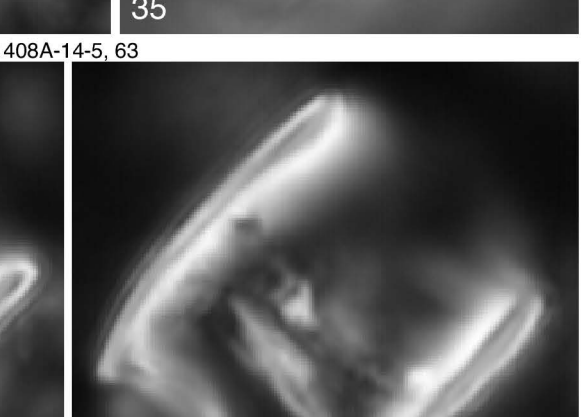
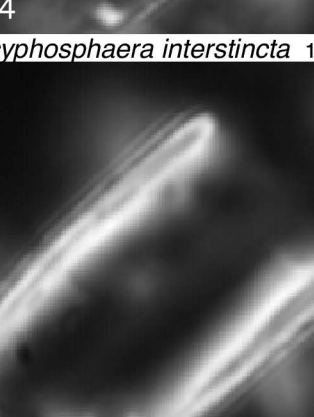
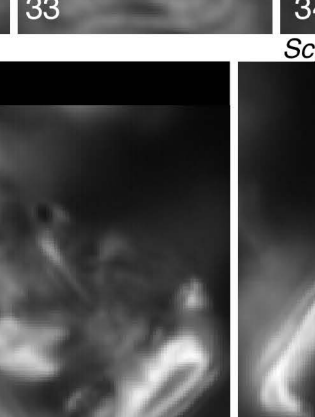
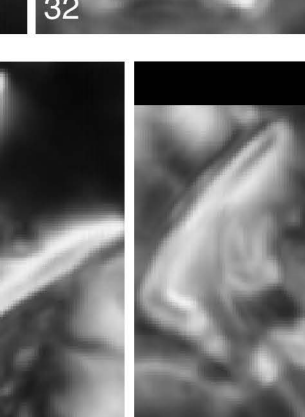
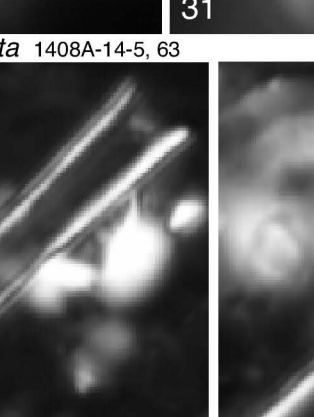
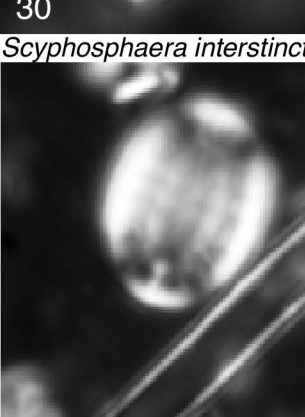
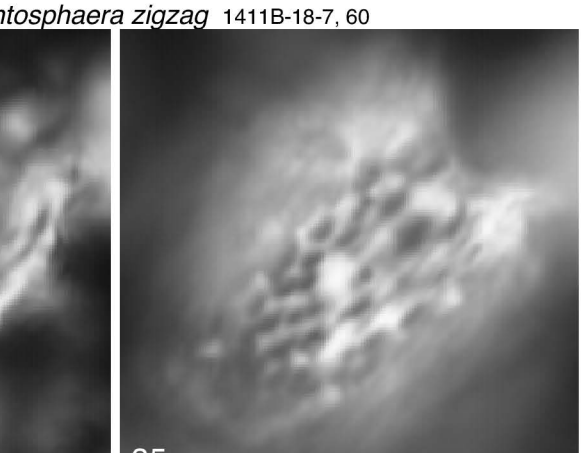
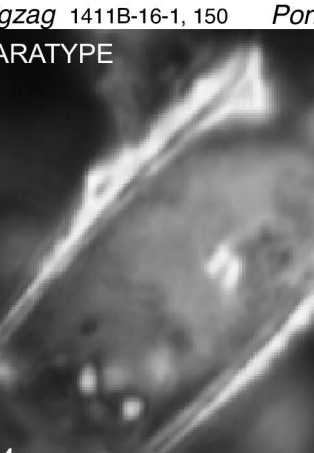
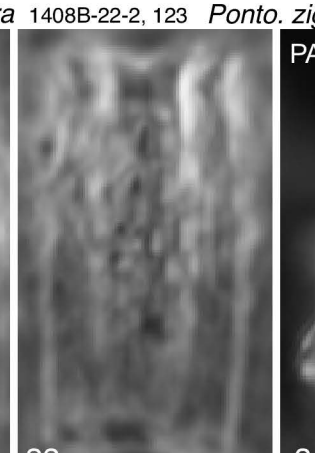
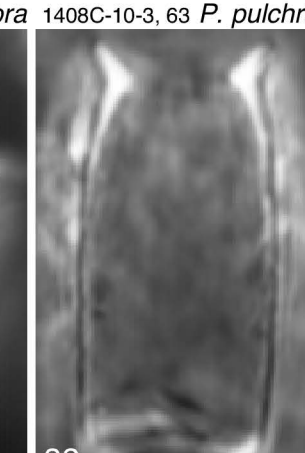
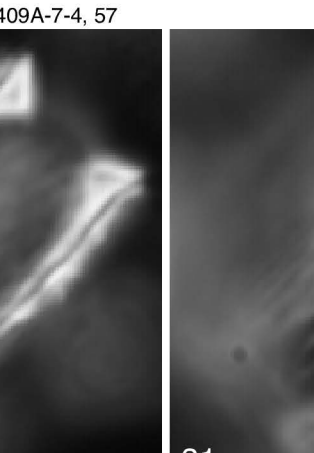
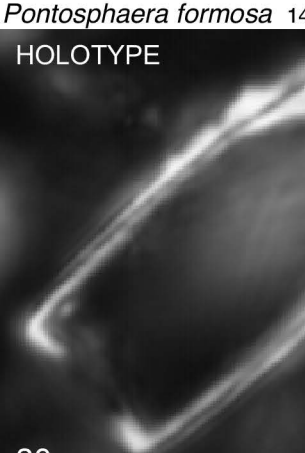
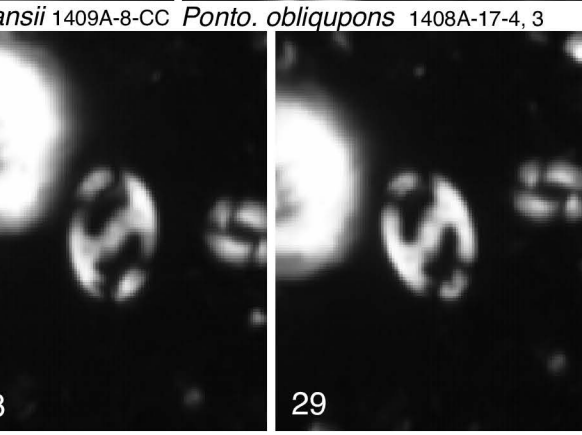
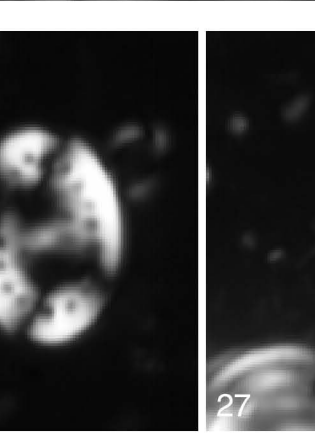
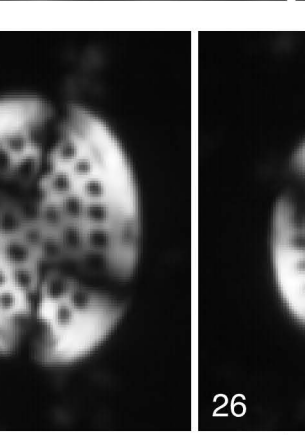
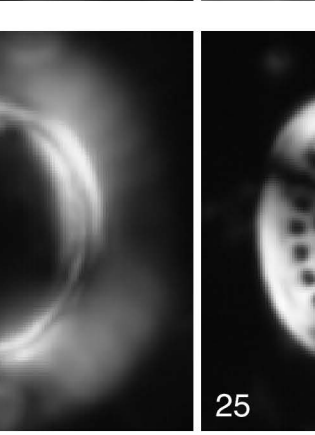
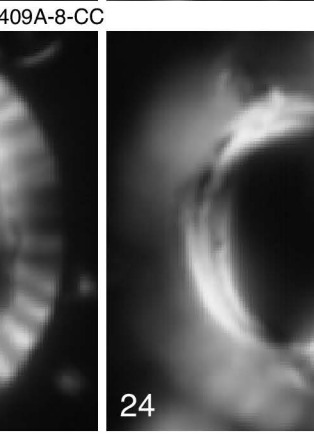
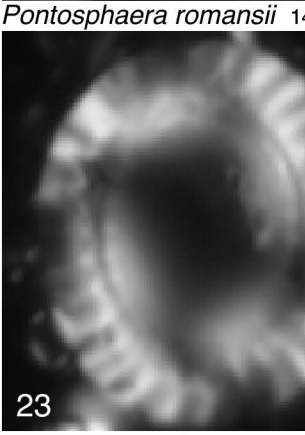
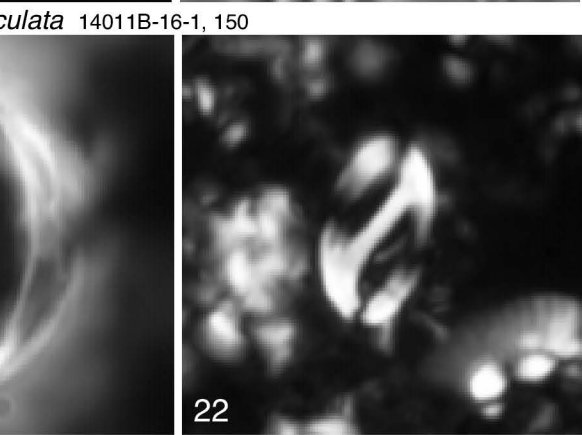
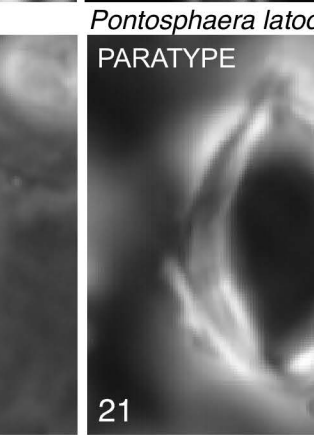
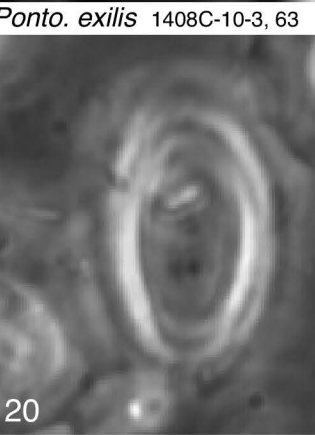
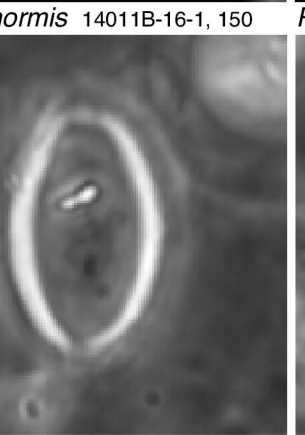
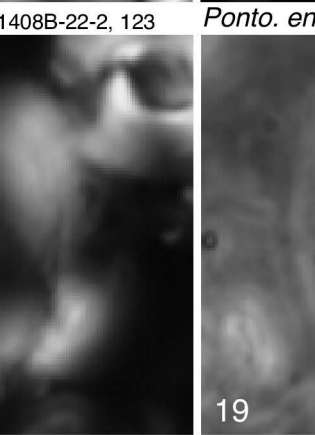
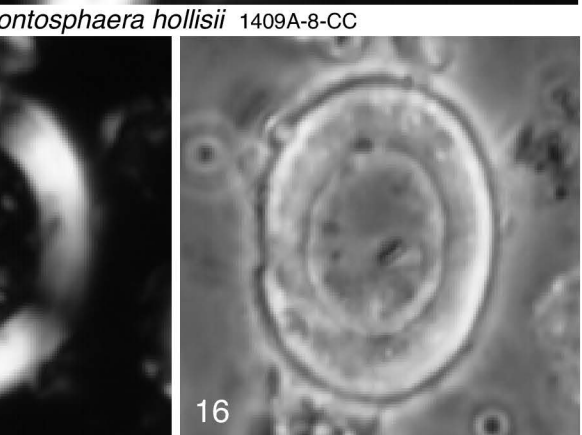
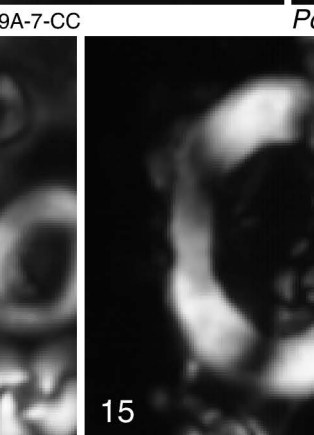
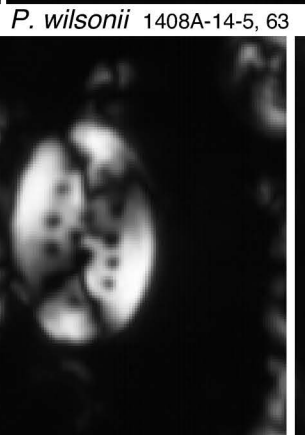
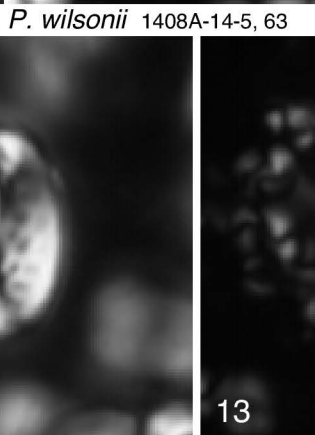
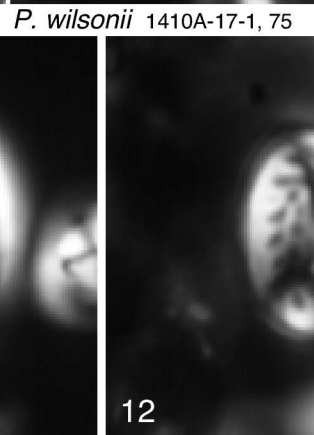
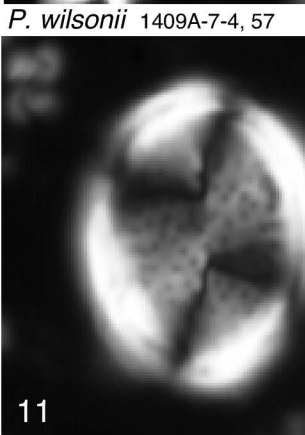


7



PARATYPE

8



2µm

Pontosphaera brinkhuisii 1409A-7-CC

Pontosphaera brinkhuisii 1409A-7-4, 57

P. wilsonii 1409A-7-4, 57

P. wilsonii 1410A-17-1, 75

P. wilsonii 1408A-14-5, 63

P. wilsonii 1408A-14-5, 63

Pontosphaera hollisii 1409A-7-CC

Pontosphaera hollisii 1409A-8-CC

Ponto. alta 14011B-16-1, 150

Po. clinosulcata 1408B-22-2, 123

Ponto. enormis 14011B-16-1, 150

Ponto. exilis 1408C-10-3, 63

Pontosphaera latoculata 14011B-16-1, 150

Pontosphaera romansii 1409A-8-CC

Pontosphaera romansii 1409A-8-CC *Ponto. obliqupons* 1408A-17-4, 3

Pontosphaera formosa 1409A-7-4, 57

P. multipora 1408C-10-3, 63 *P. pulchra* 1408B-22-2, 123

Ponto. zigzag 1411B-16-1, 150

Pontosphaera zigzag 1411B-18-7, 60

HOLOTYPE

PARATYPE

Scyphosphaera interstincta 1408A-14-5, 63

Scyphosphaera interstincta 1408A-14-5, 63

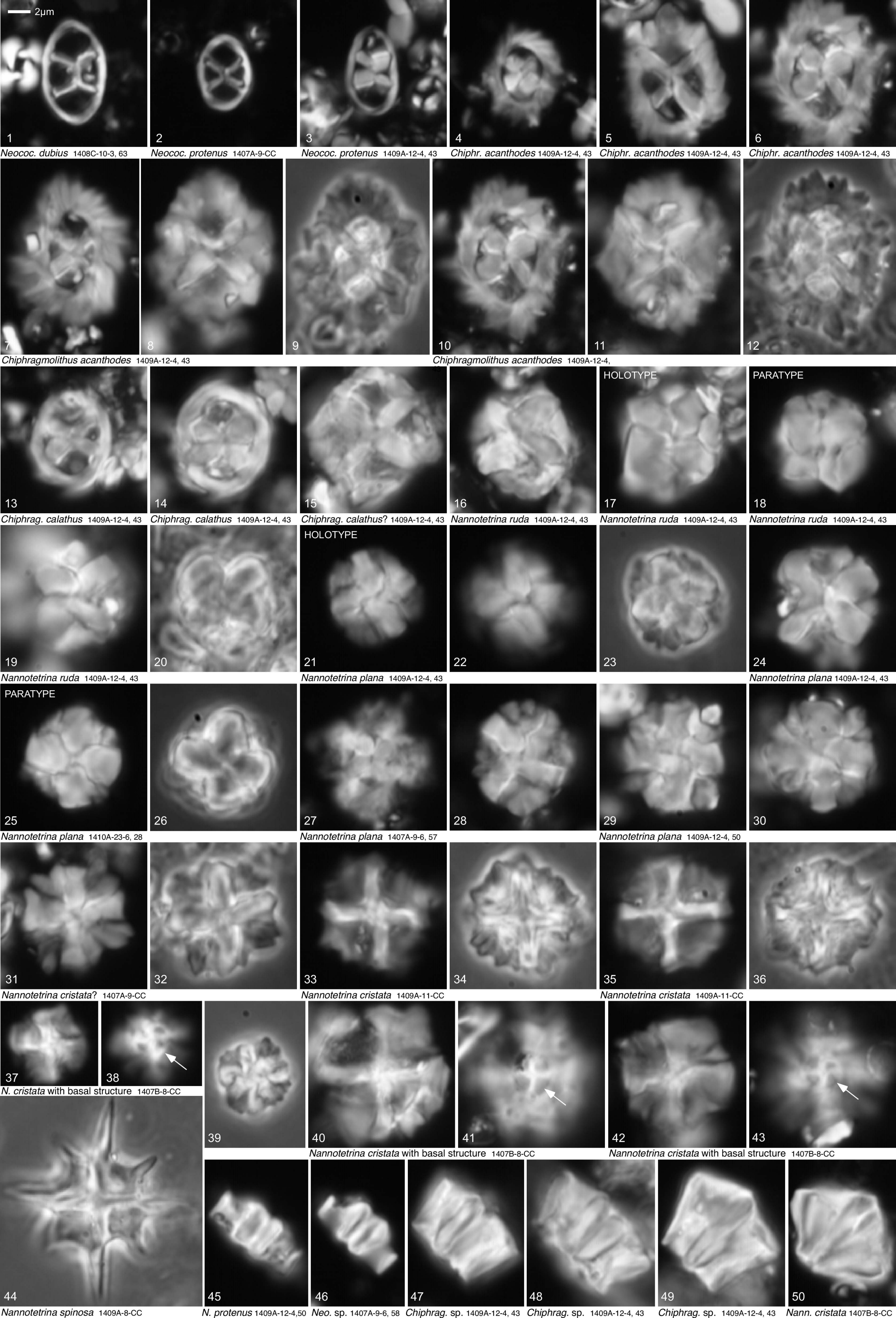
Scyphosphaera columella 1408A-7-4, 93

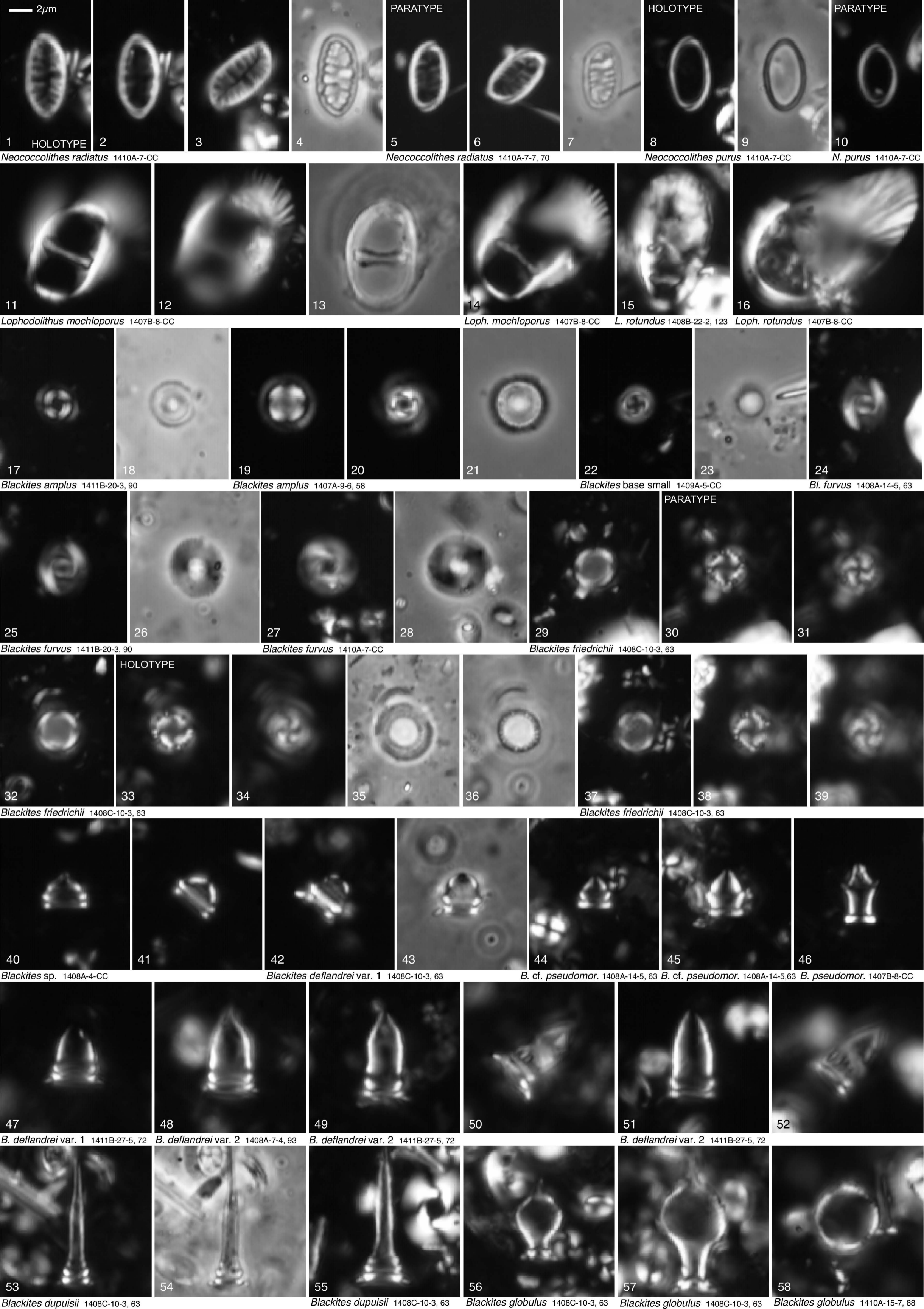
Scyphosphaera expansa 1408A-14-5, 63

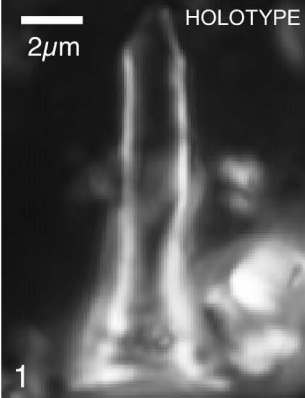
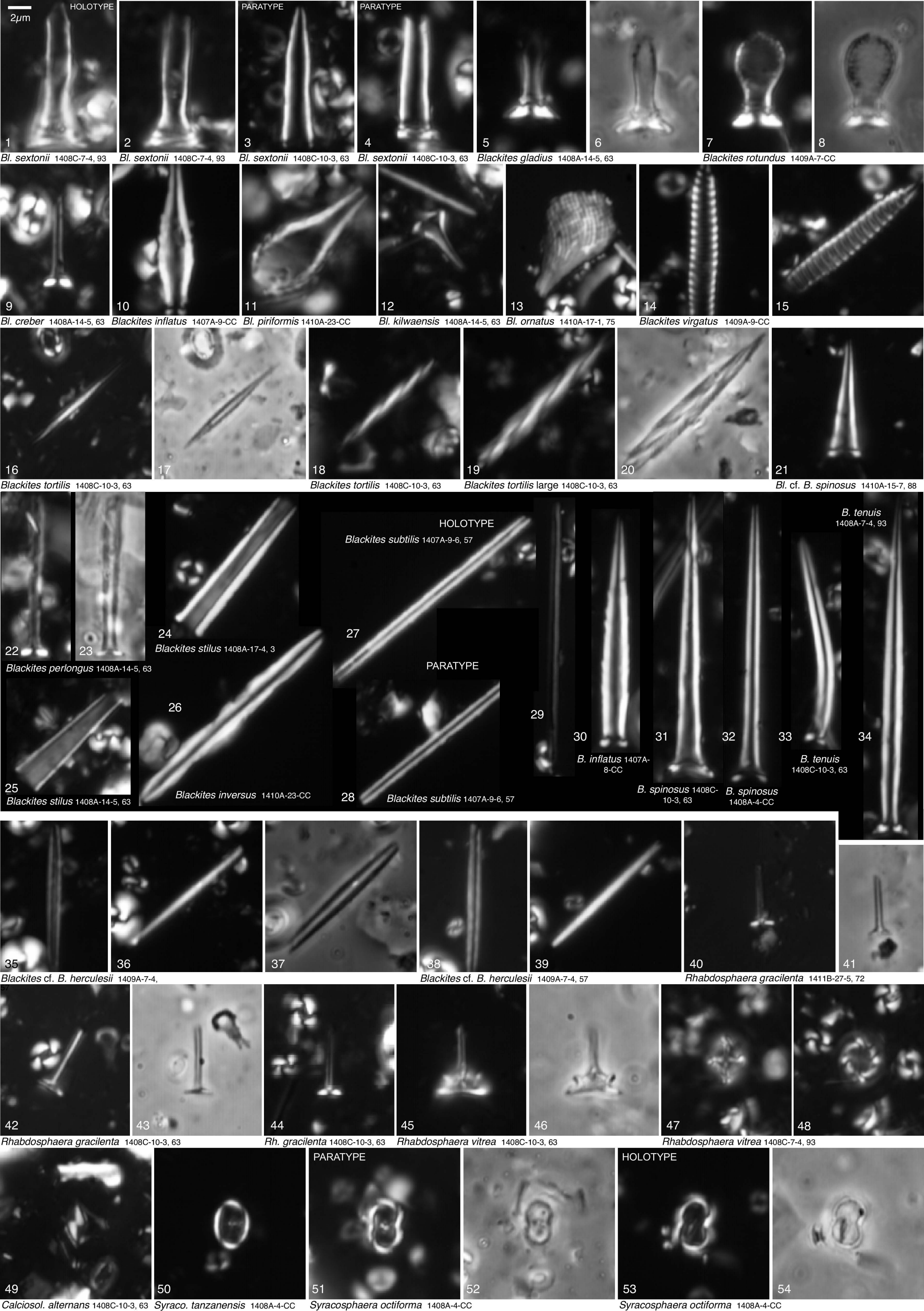
Scypho. apsteinii? 1408B-22-2, 123

Scyphosphaera apsteinii 1408A-10-3, 63

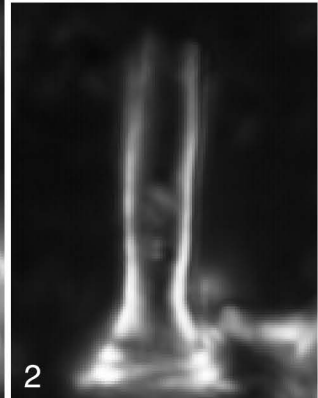
Scyphosphaera apsteinii 1408A-10-3, 63



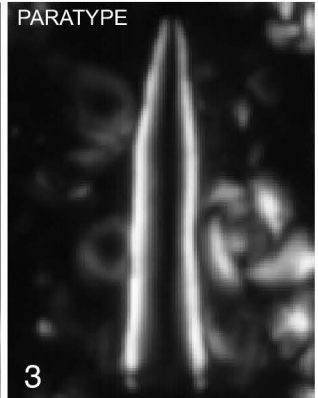




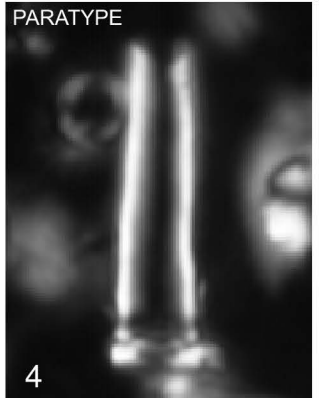
1 *Bl. sextonii* 1408C-7-4, 93



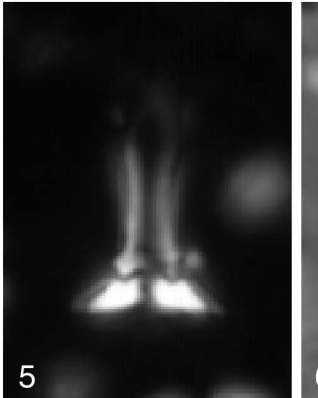
2 *Bl. sextonii* 1408C-7-4, 93



3 *Bl. sextonii* 1408C-10-3, 63



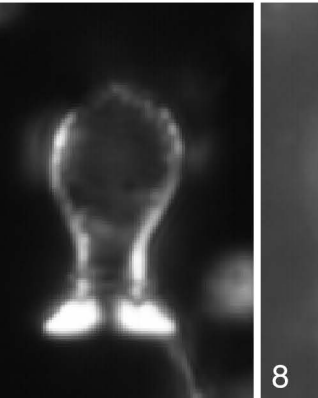
4 *Bl. sextonii* 1408C-10-3, 63



5 *Blackites gladius* 1408A-14-5, 63



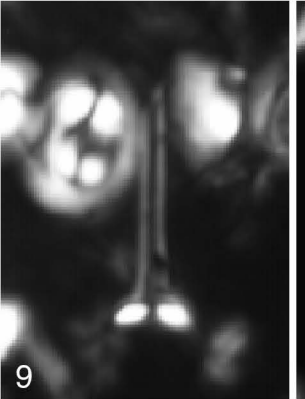
6 *Blackites gladius* 1408A-14-5, 63



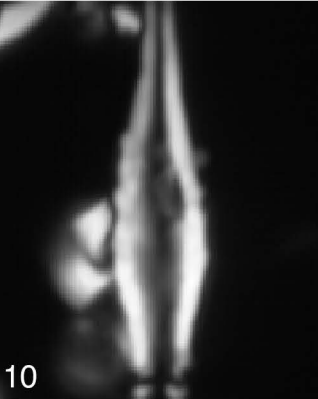
7 *Blackites rotundus* 1409A-7-CC



8 *Blackites rotundus* 1409A-7-CC



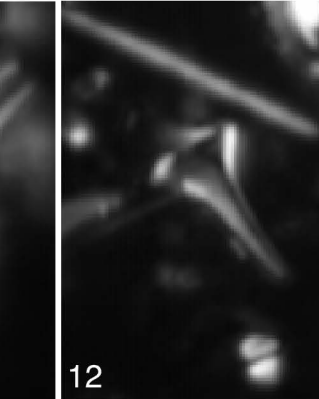
9 *Bl. creber* 1408A-14-5, 63



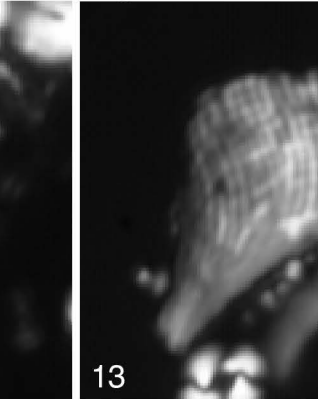
10 *Blackites inflatus* 1407A-9-CC



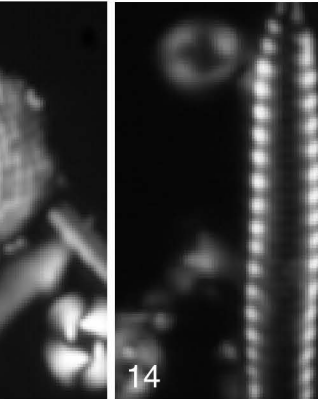
11 *Bl. piriformis* 1410A-23-CC



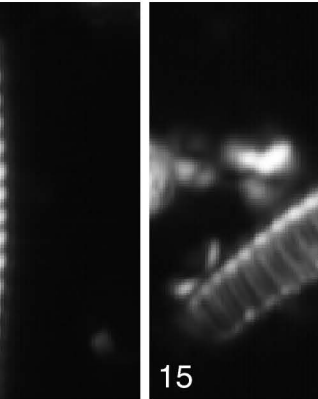
12 *Bl. kilwaensis* 1408A-14-5, 63



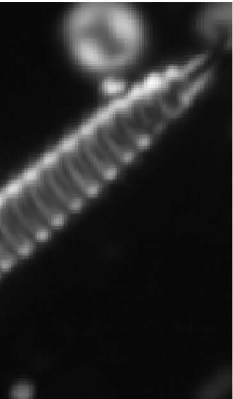
13 *Bl. ornatus* 1410A-17-1, 75



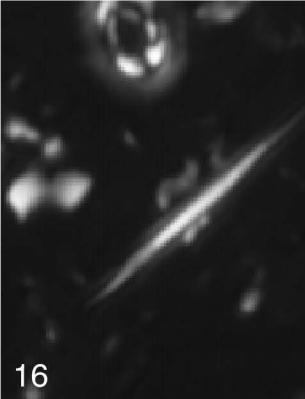
14 *Blackites virgatus* 1409A-9-CC



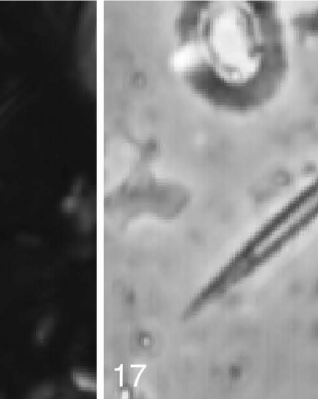
15 *Blackites virgatus* 1409A-9-CC



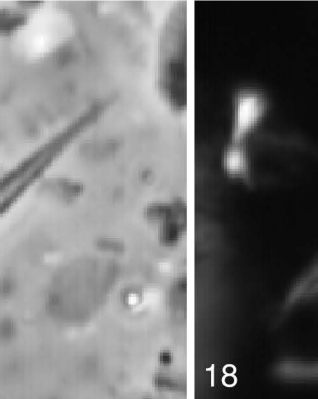
16 *Blackites tortilis* 1408C-10-3, 63



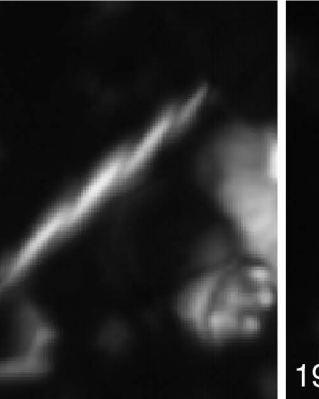
17 *Blackites tortilis* 1408C-10-3, 63



18 *Blackites tortilis* 1408C-10-3, 63



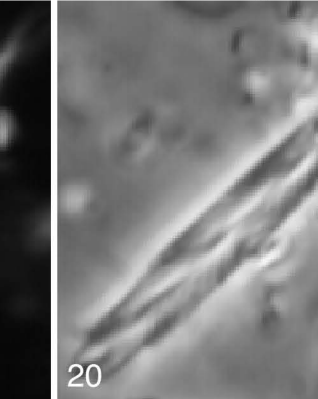
19 *Blackites tortilis large* 1408C-10-3, 63



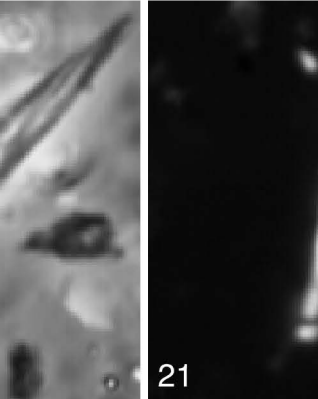
20 *Blackites tortilis large* 1408C-10-3, 63



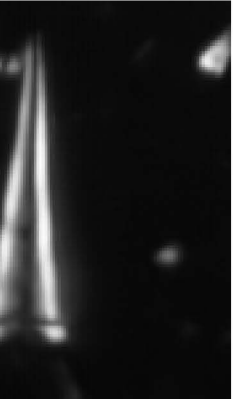
21 *Bl. cf. B. spinosus* 1410A-15-7, 88



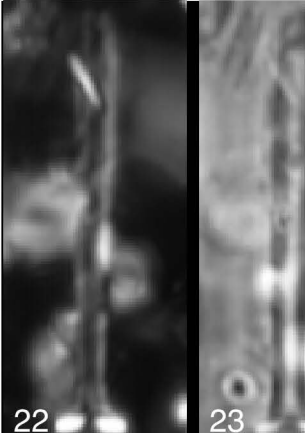
22 *Blackites perlongus* 1408A-14-5, 63



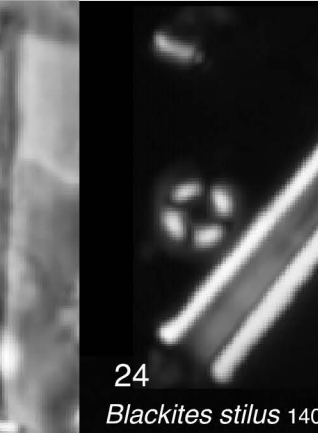
23 *Blackites perlongus* 1408A-14-5, 63



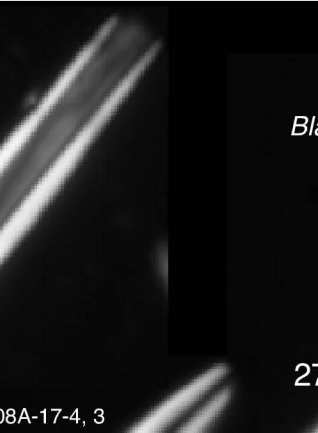
24 *Blackites stilus* 1408A-17-4, 3



25 *Blackites stilus* 1408A-14-5, 63



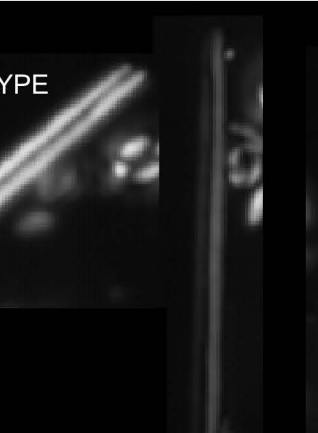
26 *Blackites inversus* 1410A-23-CC



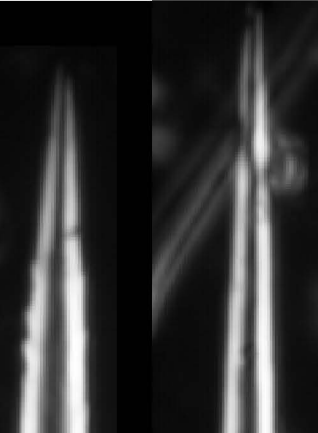
27 *Blackites subtilis* 1407A-9-6, 57



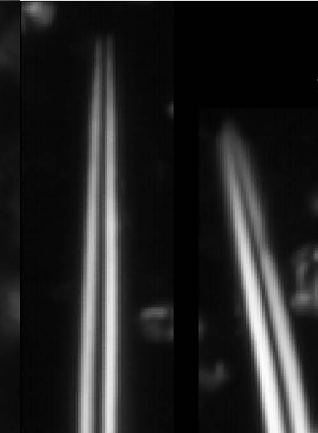
28 *Blackites subtilis* 1407A-9-6, 57



29 *B. inflatus* 1407A-8-CC



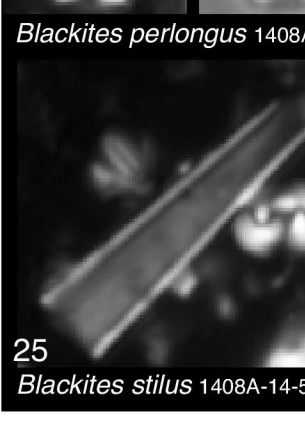
30 *B. spinosus* 1408C-10-3, 63



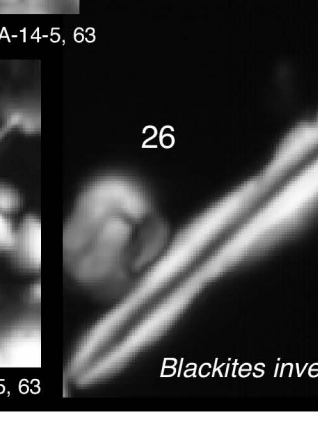
31 *B. spinosus* 1408A-4-CC



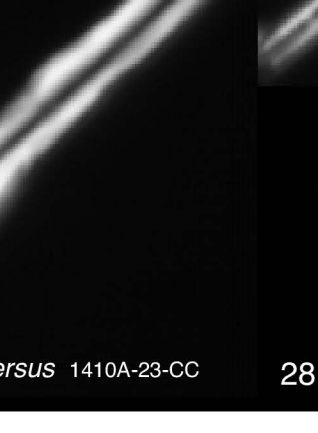
32 *B. spinosus* 1408C-10-3, 63



33 *B. tenuis* 1408A-7-4, 93



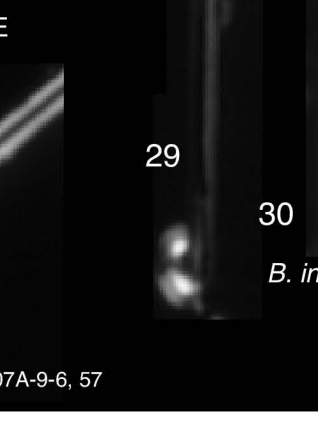
34 *B. tenuis* 1408C-10-3, 63



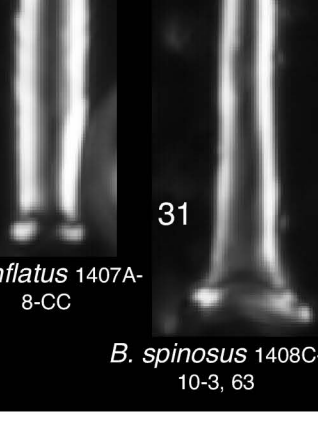
35 *Blackites cf. B. herculesii* 1409A-7-4,



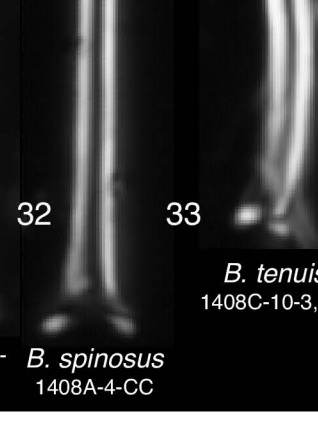
36 *Blackites cf. B. herculesii* 1409A-7-4, 57



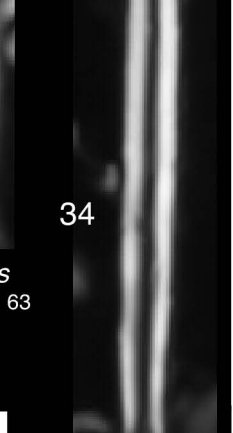
37 *Rhabdosphaera gracilentia* 1411B-27-5, 72



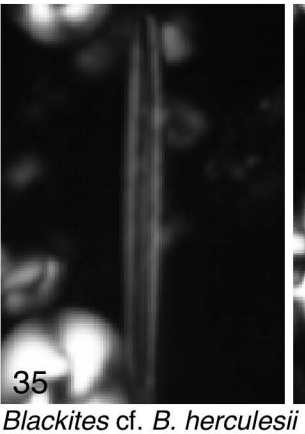
38 *Rhabdosphaera vitrea* 1408C-10-3, 63



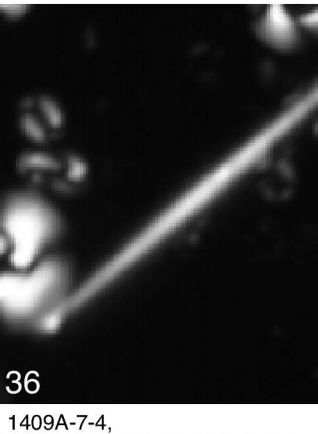
39 *Rhabdosphaera vitrea* 1408C-10-3, 63



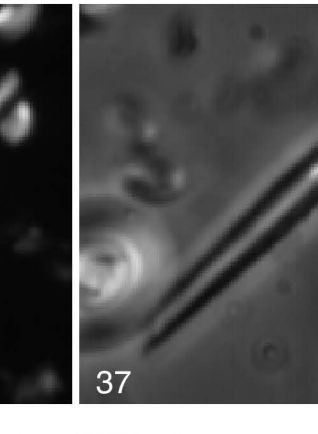
40 *Rhabdosphaera vitrea* 1408C-7-4, 93



41 *Rhabdosphaera vitrea* 1408C-7-4, 93



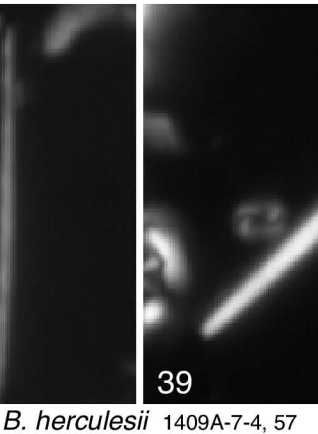
42 *Rhabdosphaera gracilentia* 1408C-10-3, 63



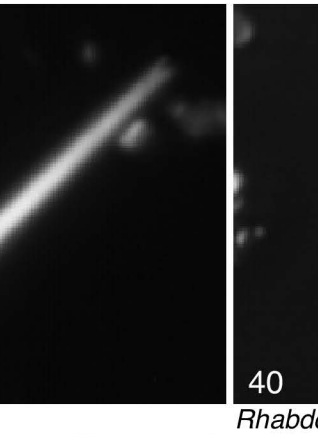
43 *Rh. gracilentia* 1408C-10-3, 63



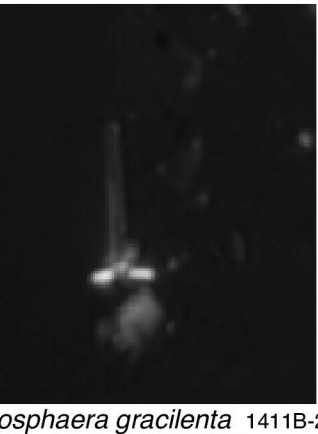
44 *Rhabdosphaera vitrea* 1408C-10-3, 63



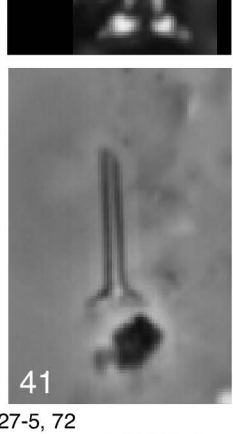
45 *Rhabdosphaera vitrea* 1408C-10-3, 63



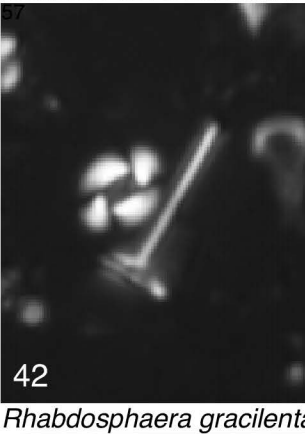
46 *Rhabdosphaera vitrea* 1408C-10-3, 63



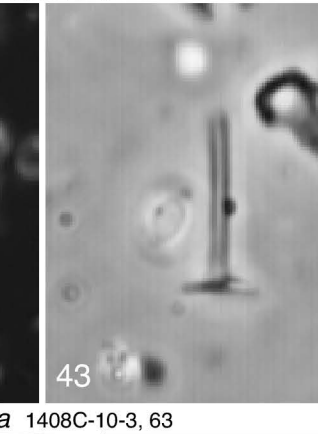
47 *Rhabdosphaera vitrea* 1408C-7-4, 93



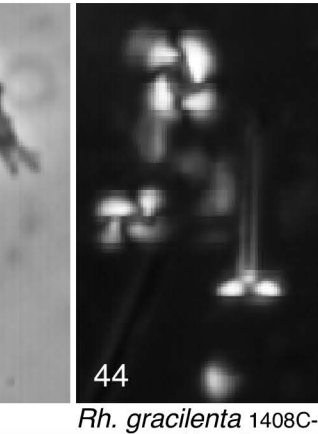
48 *Rhabdosphaera vitrea* 1408C-7-4, 93



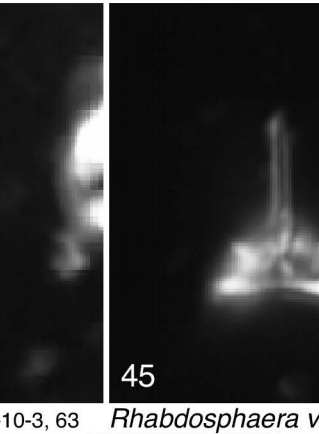
49 *Calciol. alternans* 1408C-10-3, 63



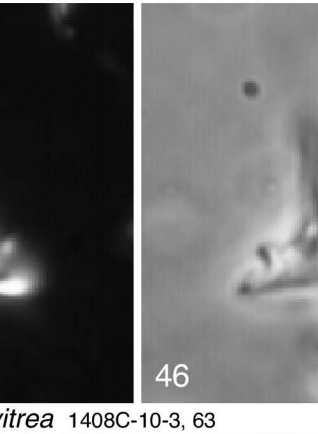
50 *Syraco. tanzanensis* 1408A-4-CC



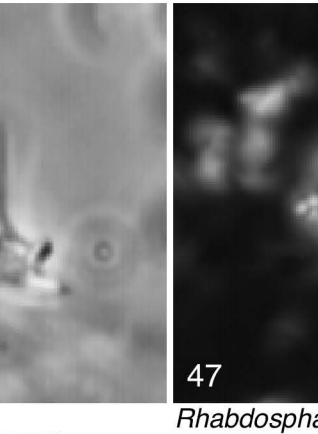
51 *Syracosphaera octiforma* 1408A-4-CC



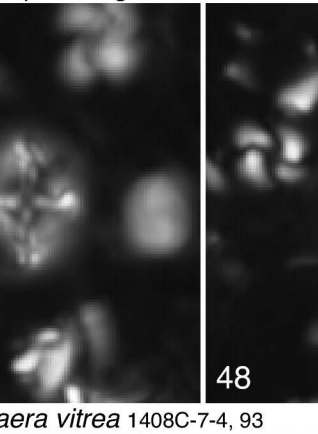
52 *Syracosphaera octiforma* 1408A-4-CC



53 *Syracosphaera octiforma* 1408A-4-CC



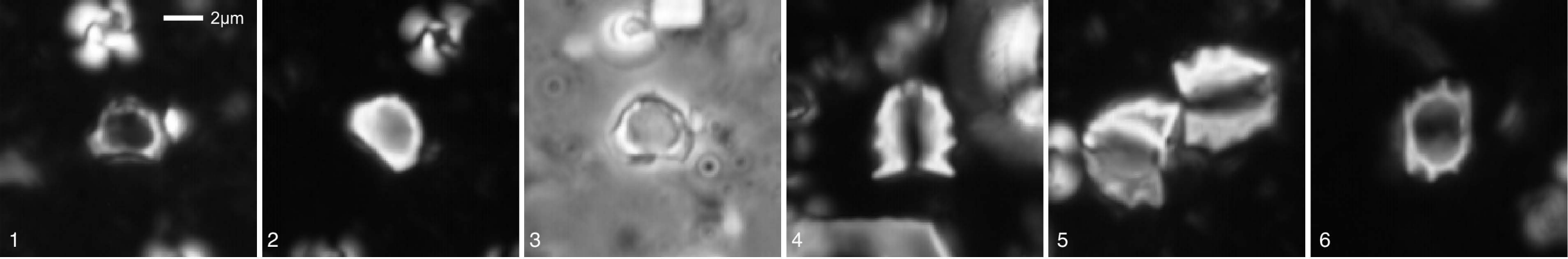
54 *Syracosphaera octiforma* 1408A-4-CC



55 *Syracosphaera octiforma* 1408A-4-CC



56 *Syracosphaera octiforma* 1408A-4-CC



1 *Dakylethra unitatis* 1408B-22-2, 123

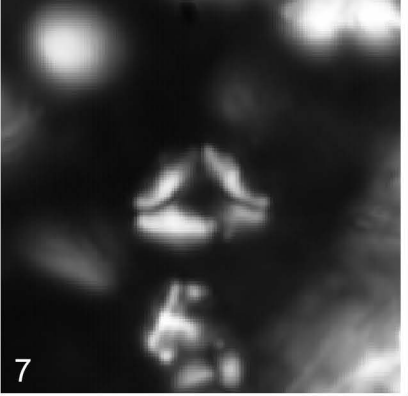
2 *Dakylethra unitatis* 1408B-22-2, 123

3 *Dakylethra unitatis* 1408B-22-2, 123

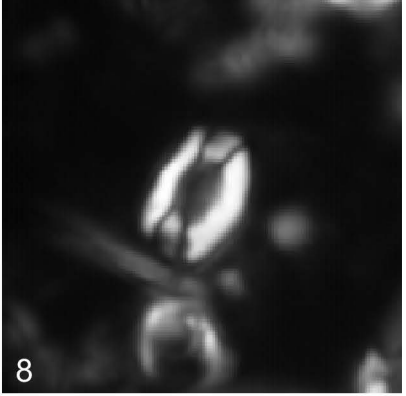
4 *Dakyl. punctulata* 1408C-10-3, 63

5 *Dakyl. punctulata* 1408C-10-3, 63

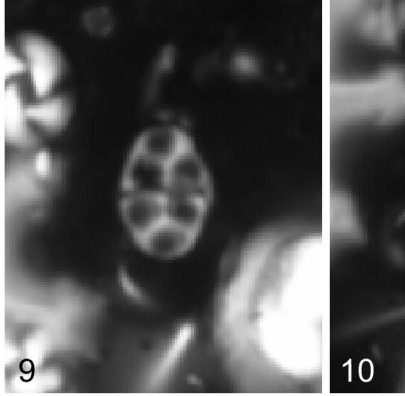
6 *Dakyl. punctulata* 1408C-10-3, 63



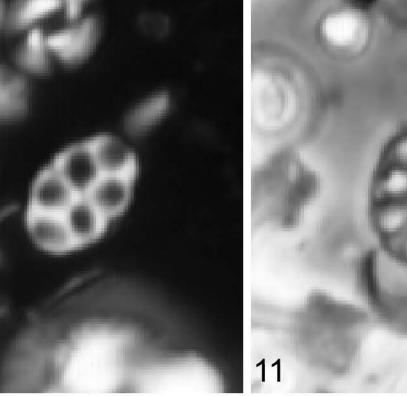
7 *Lanternithus minutus* 1408C-10-3, 63



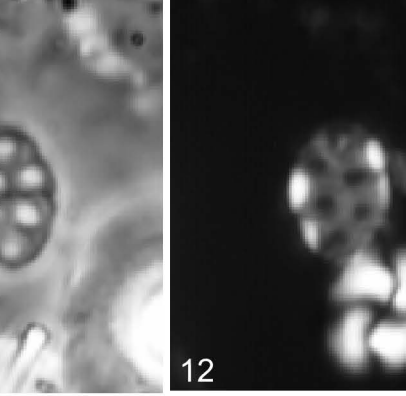
8 *Lantern. minutus* 1408C-10-3, 63



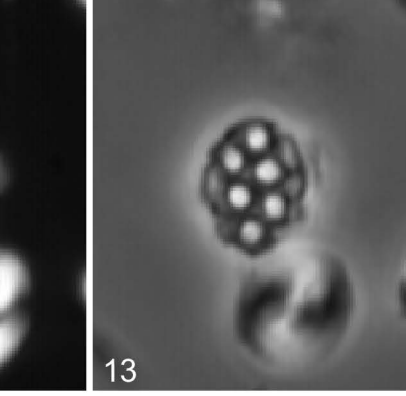
9 *Holodiscolithus solidus* 1408C-10-3, 63



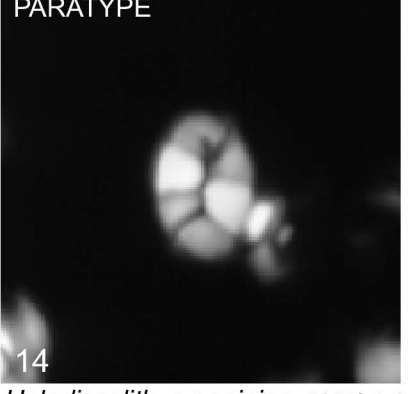
10 *Holodiscolithus solidus* 1408C-10-3, 63



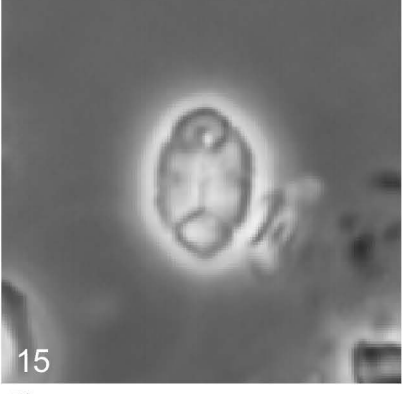
11 *Holodiscolithus solidus* 1408C-10-3, 63



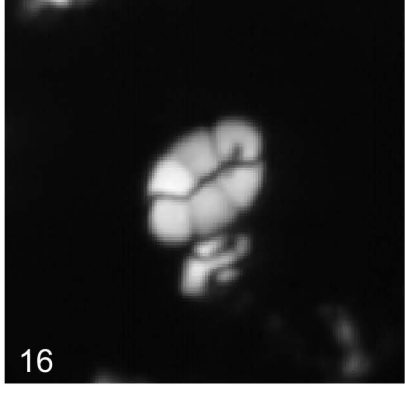
12 *Holodiscolithus solidus* 1408C-10-3, 63



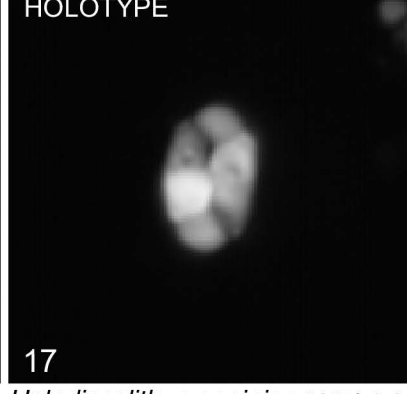
14 *Holodiscolithus agninae* 1407A-9-6, 58



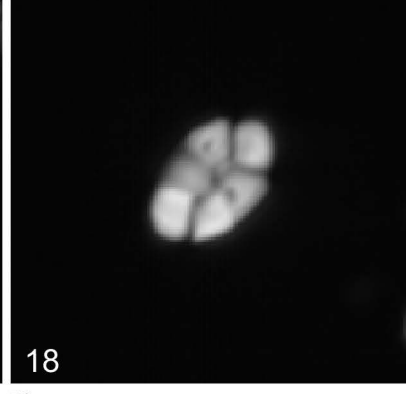
15 *Holodiscolithus agninae* 1407A-9-6, 58



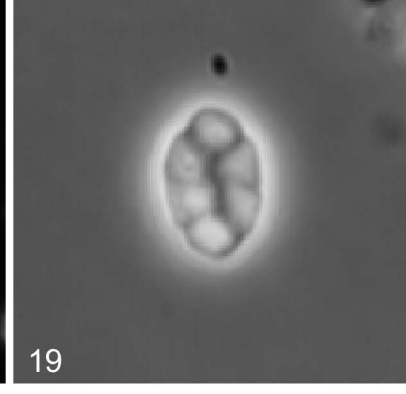
16 *Holodiscolithus agninae* 1407A-9-6, 58



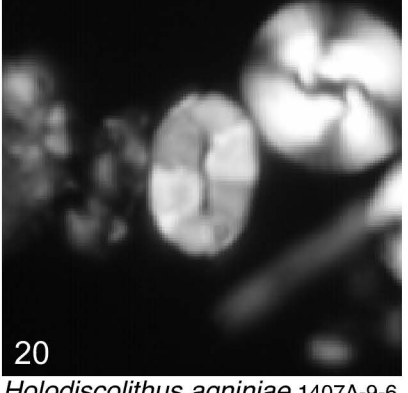
17 *Holodiscolithus agninae* 1407A-9-6, 58



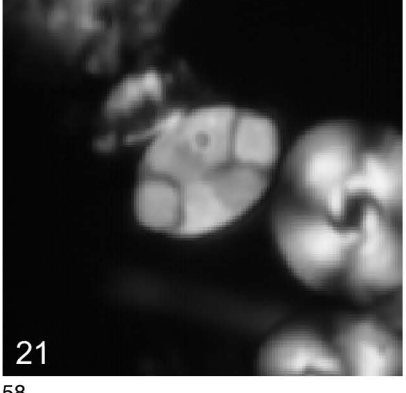
18 *Holodiscolithus agninae* 1407A-9-6, 58



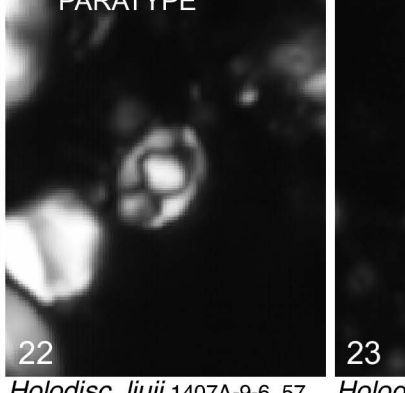
19 *Holodiscolithus agninae* 1407B-8-CC



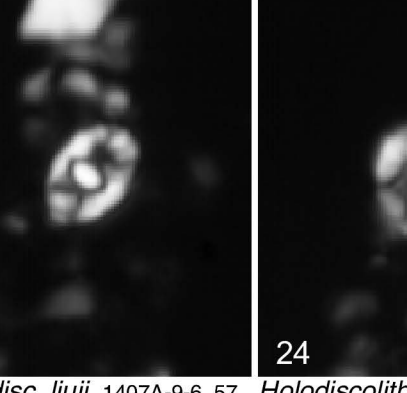
20 *Holodiscolithus agninae* 1407A-9-6, 58



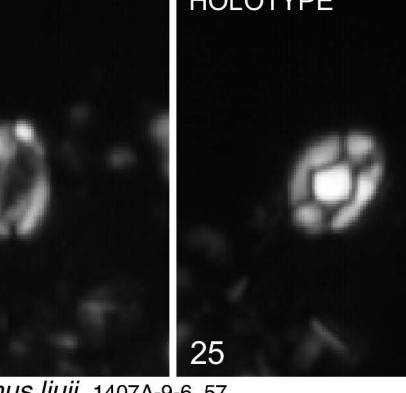
21 *Holodiscolithus agninae* 1407A-9-6, 58



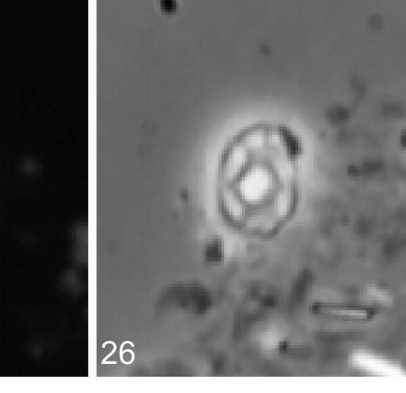
22 *Holodisc. liuii* 1407A-9-6, 57



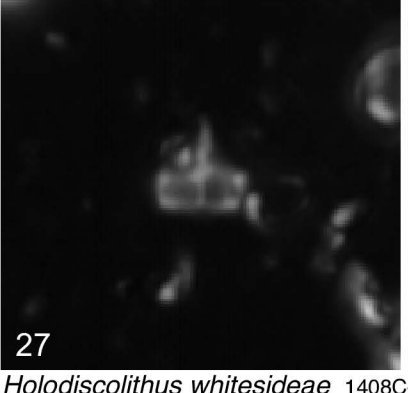
23 *Holodisc. liuii* 1407A-9-6, 57



24 *Holodiscolithus liuii* 1407A-9-6, 57



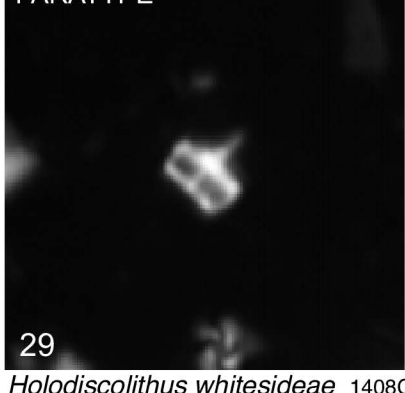
25 *Holodiscolithus liuii* 1407A-9-6, 57



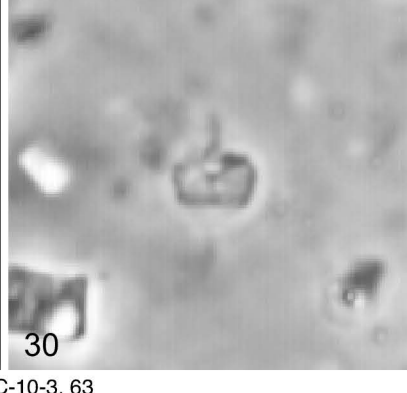
27 *Holodiscolithus whitesideae* 1408C-10-3, 63



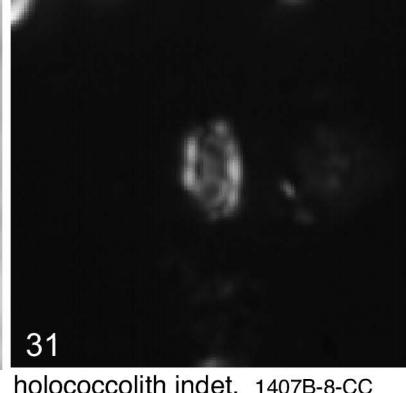
28 *Holodiscolithus whitesideae* 1408C-10-3, 63



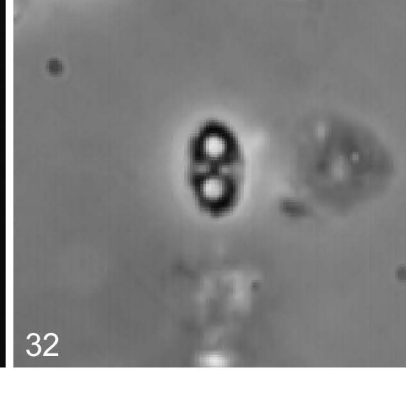
29 *Holodiscolithus whitesideae* 1408C-10-3, 63



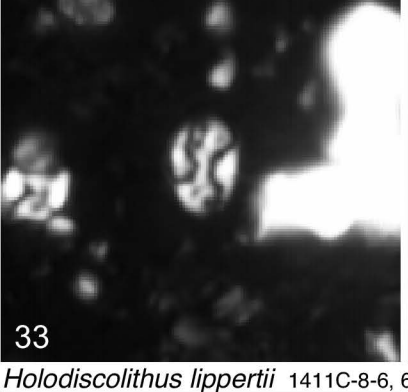
30 *holococcolith indet.* 1407B-8-CC



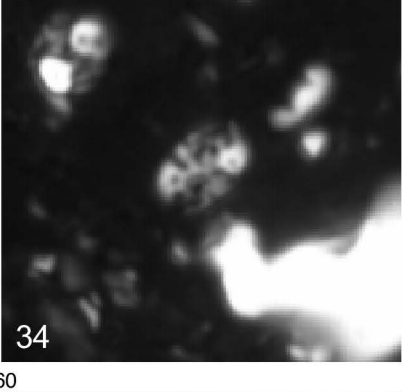
31 *holococcolith indet.* 1407B-8-CC



32 *holococcolith indet.* 1407B-8-CC



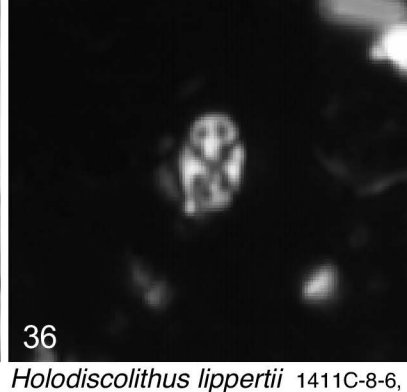
33 *Holodiscolithus lippertii* 1411C-8-6, 60



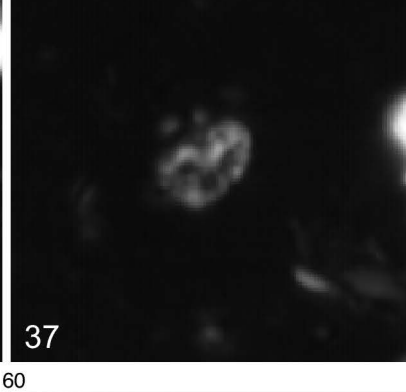
34 *Holodiscolithus lippertii* 1411C-8-6, 60



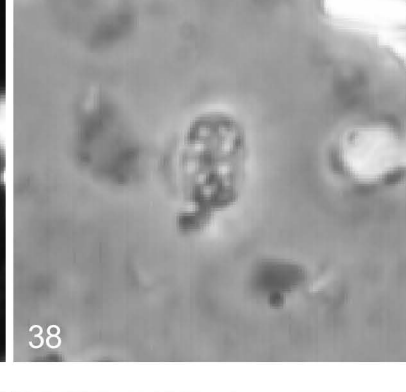
35 *Holodiscolithus lippertii* 1411C-8-6, 60



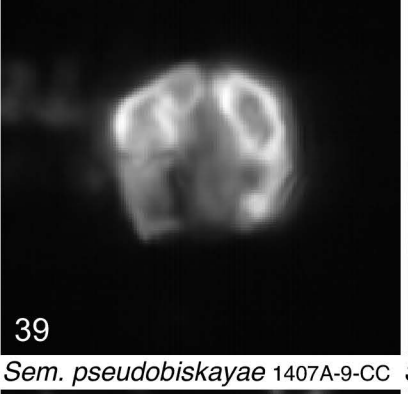
36 *Holodiscolithus lippertii* 1411C-8-6, 60



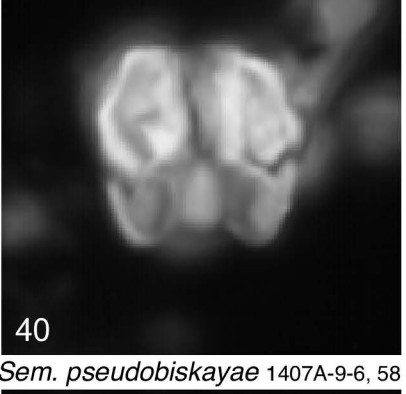
37 *Holodiscolithus lippertii* 1411C-8-6, 60



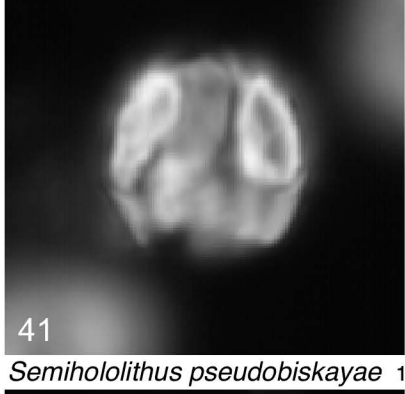
38 *Holodiscolithus lippertii* 1411C-8-6, 60



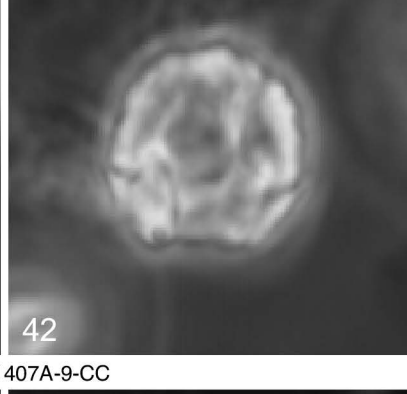
39 *Sem. pseudobiskayae* 1407A-9-CC



40 *Sem. pseudobiskayae* 1407A-9-6, 58



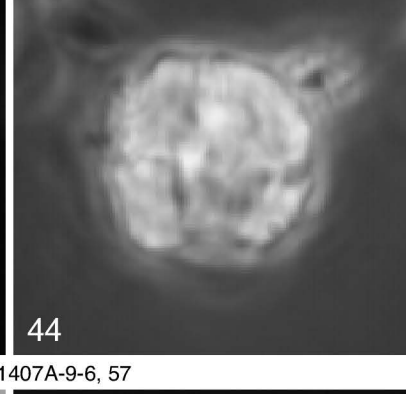
41 *Semihololithus pseudobiskayae* 1407A-9-CC



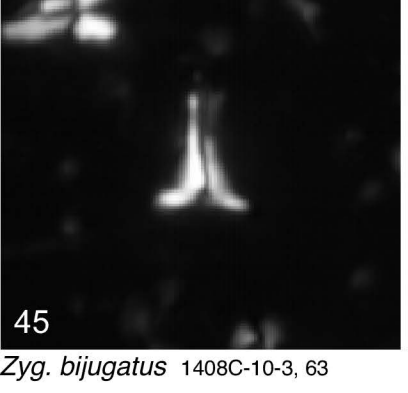
42 *Semihololithus pseudobiskayae* 1407A-9-6, 57



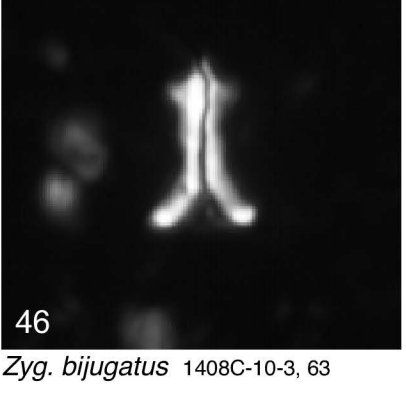
43 *Semihololithus pseudobiskayae* 1407A-9-6, 57



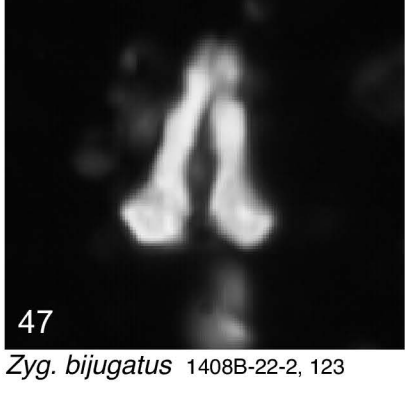
44 *Semihololithus pseudobiskayae* 1407A-9-6, 57



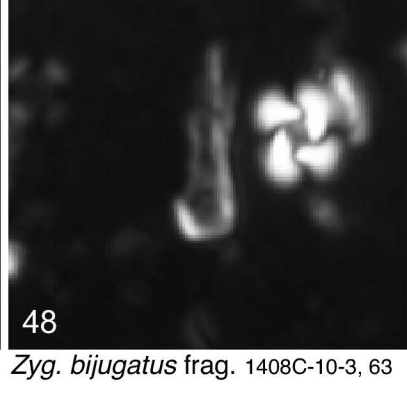
45 *Zyg. bijugatus* 1408C-10-3, 63



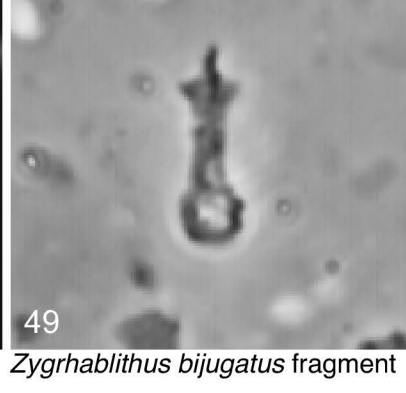
46 *Zyg. bijugatus* 1408C-10-3, 63



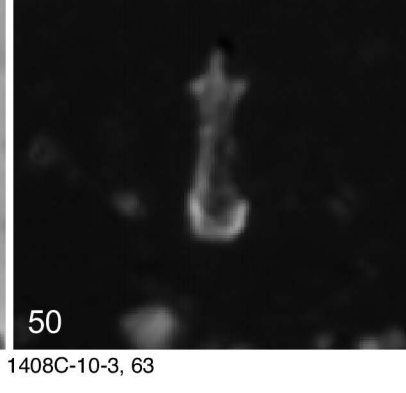
47 *Zyg. bijugatus* 1408B-22-2, 123



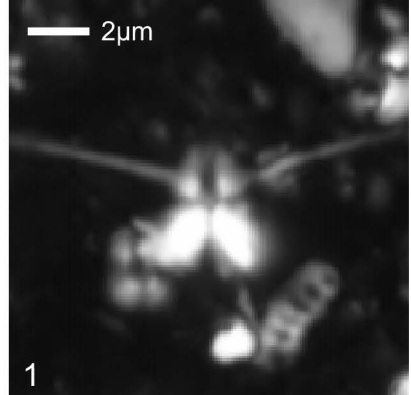
48 *Zyg. bijugatus frag.* 1408C-10-3, 63



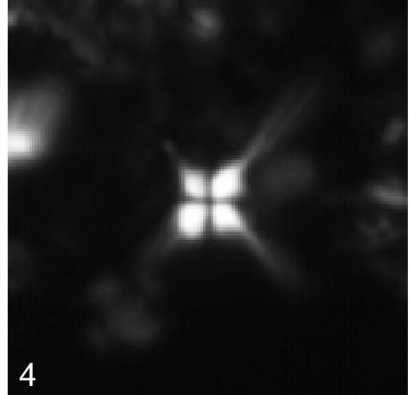
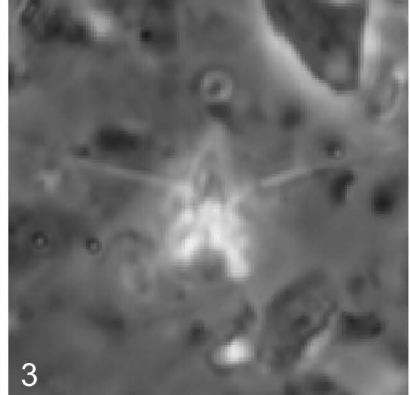
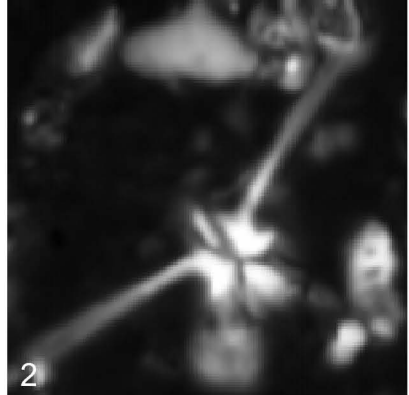
49 *Zygrhablithus bijugatus fragment* 1408C-10-3, 63



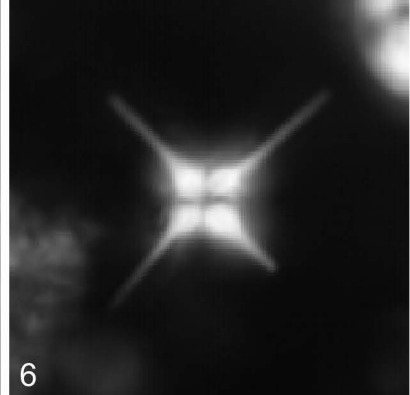
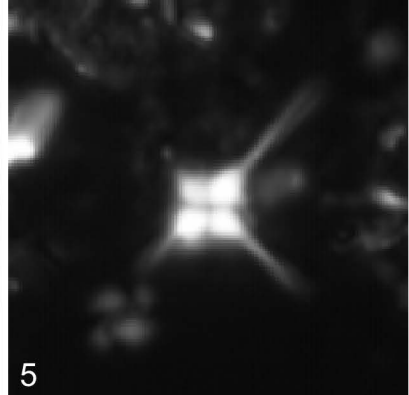
50 *Zygrhablithus bijugatus fragment* 1408C-10-3, 63



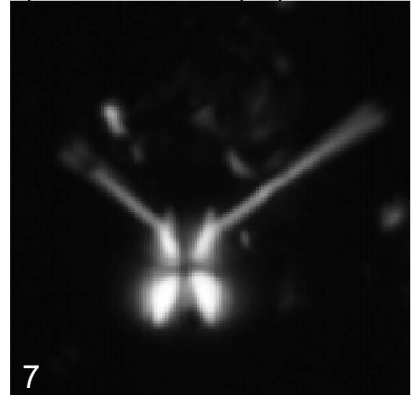
1 *Sphenolithus* cf. *S. perpendicularis* 1408B-22-2, 123



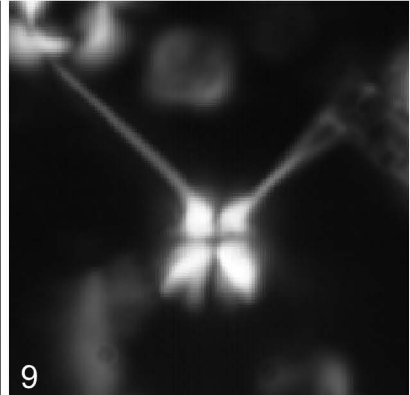
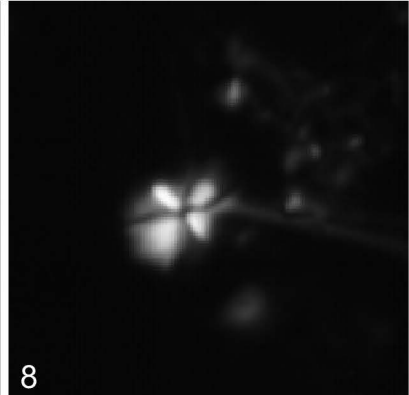
4 *Sphenolithus* cf. *S. kempii* 1407B-8-CC



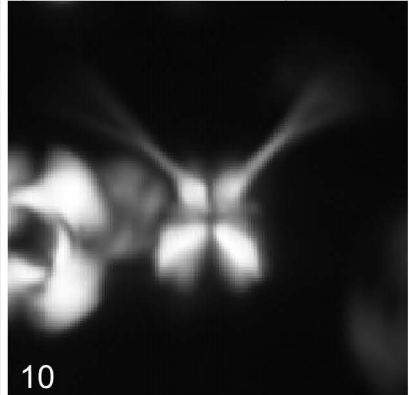
6 *Spheno.* cf. *S. kempii* 1409A-9-CC



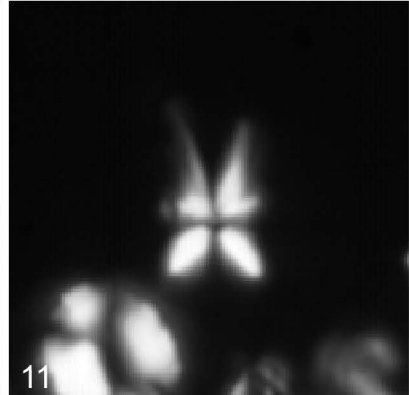
7 *Sphenolithus perpendicularis* 1409A-9-CC



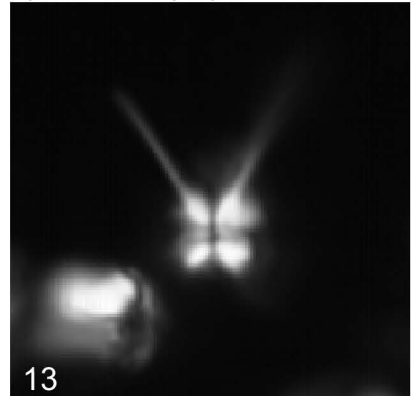
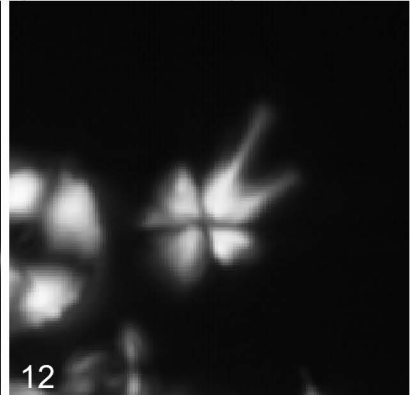
9 *Sph. perpendicularis* 1409A-9-CC



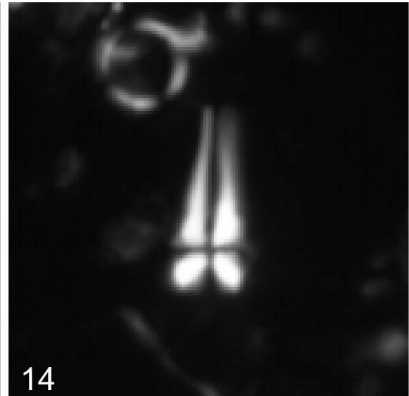
10 *Sph. perpendicularis* 1409A-9-CC



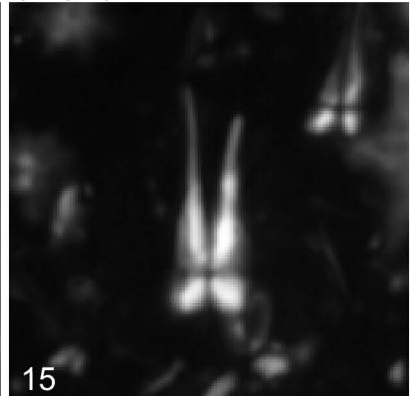
11 *Sphenolithus perpendicularis* 1407B-8-CC



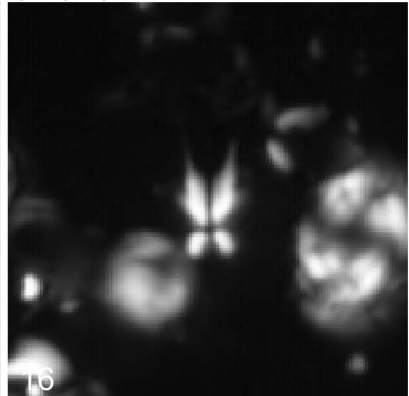
13 *Sph. perpendicularis* 1407B-8-CC



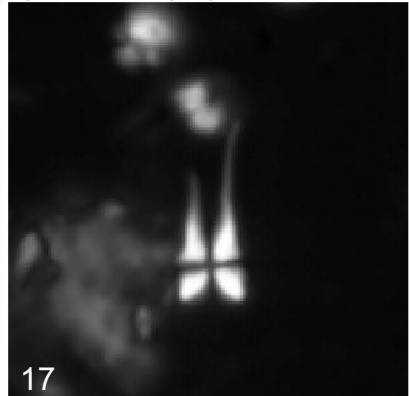
14 *S. cf. S. furcatolithoides* 1410A-18-CC



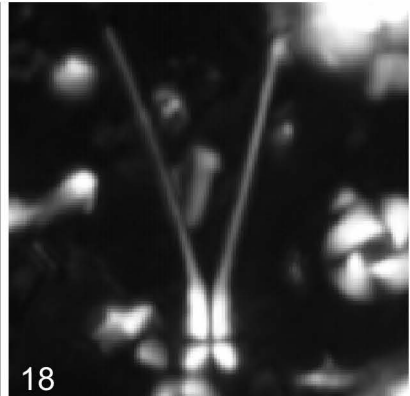
15 *S. furcatolithoides* 1410A-18-CC



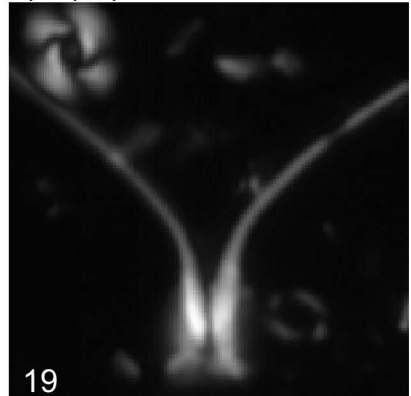
16 *S. furcatolithoides* 1408C-10-3, 63



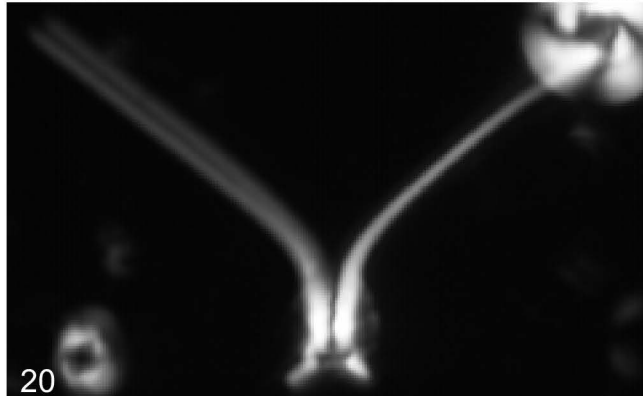
17 *S. furcatolithoides* 1408B-22-2, 123



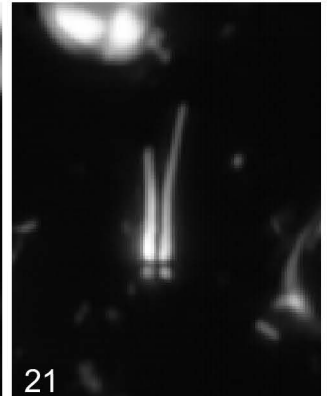
18 *S. furcatolithoides* 1408B-22-2, 123



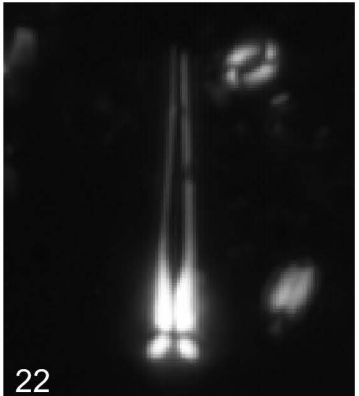
19 *Spheno. cuniculus* 1409A-6-CC



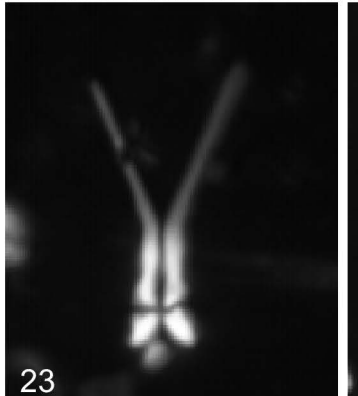
20 *Sphenolithus cuniculus* 1409A-7-4, 57



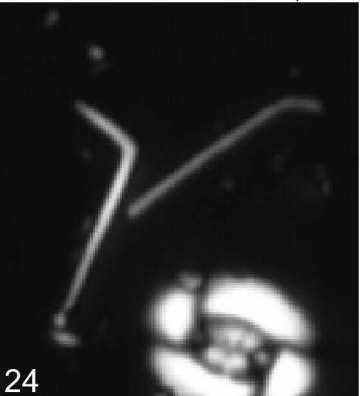
21 *S. furcatolithoides* 1409A-6-CC



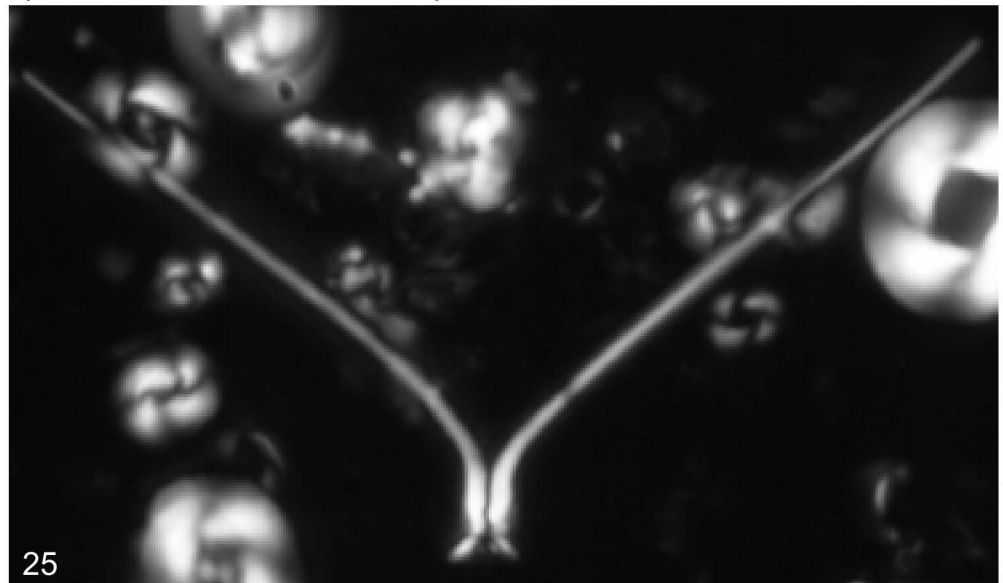
22 *S. furcatolithoides* 1409A-7-4, 57



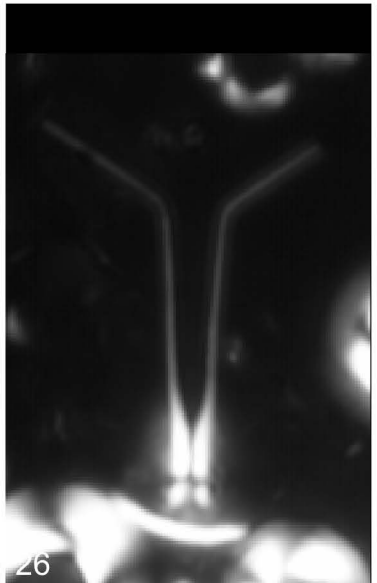
23 *S. strigosus* 1408C-10-3, 63



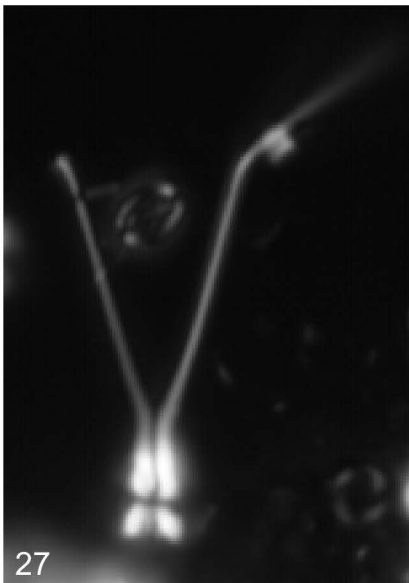
24 *spheno. spines* 1411B-27-5, 72



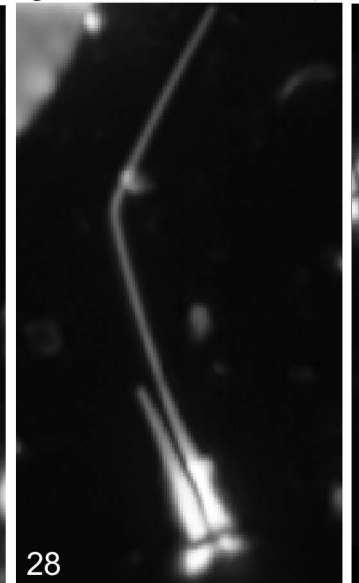
25 *Sphenolithus cuniculus* 1409A-7-CC



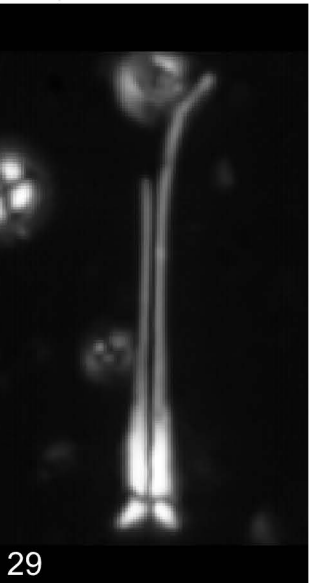
26 *S. furcatolithoides* 1409A-7-4, 57



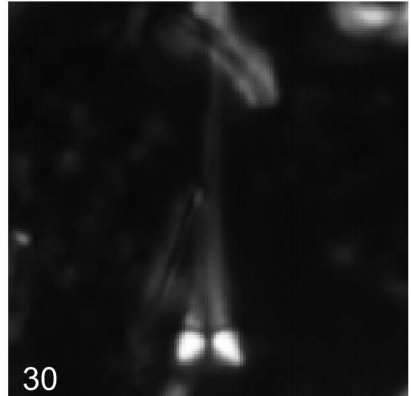
27 *Sphenolithus strigosus* 1409A-5-CC



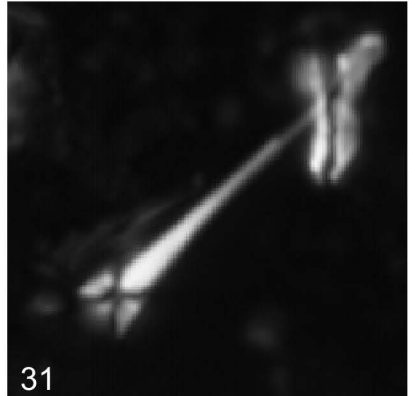
28 *S. strigosus* 1408A-14-5, 63



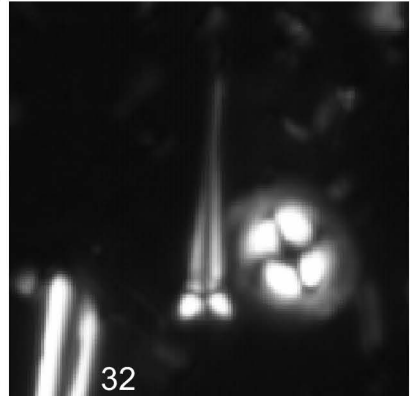
29 *S. strigosus* 1408A-14-5, 63



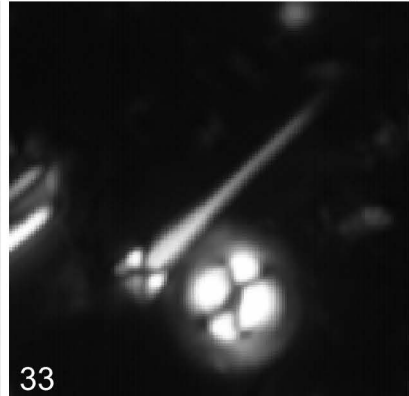
30 *Sphenolithus runus* 1408A-14-5, 63



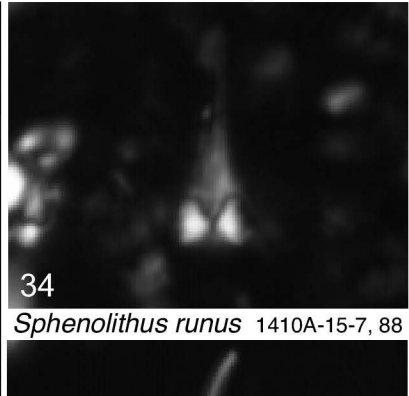
31 *Sphenolithus runus* 1408A-14-5, 63



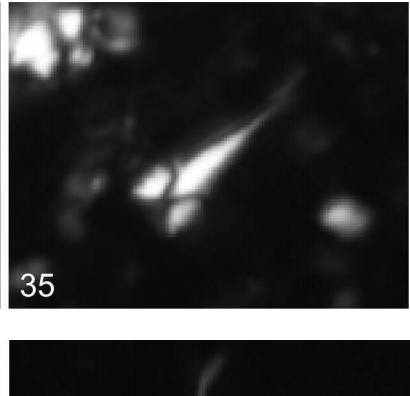
32 *Sphenolithus runus* 1408A-14-5, 63



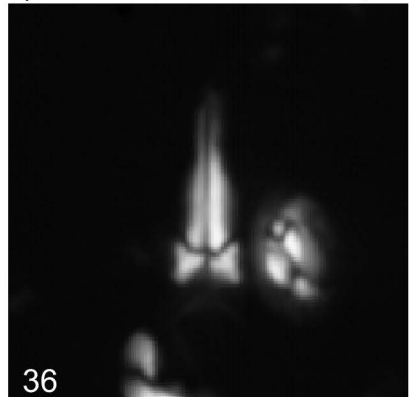
33 *Sphenolithus runus* 1408A-14-5, 63



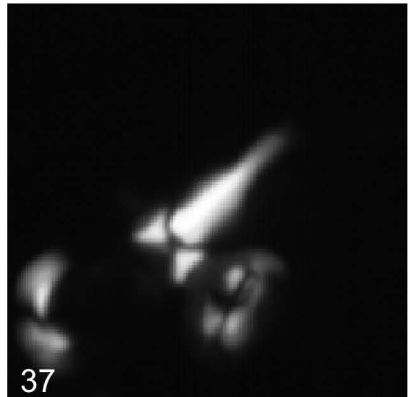
34 *Sphenolithus runus* 1410A-15-7, 88



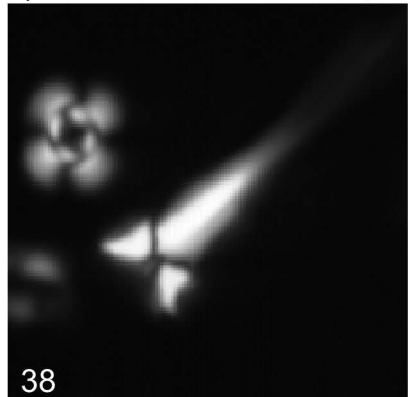
35 *Sphenolithus runus* 1410A-15-7, 88



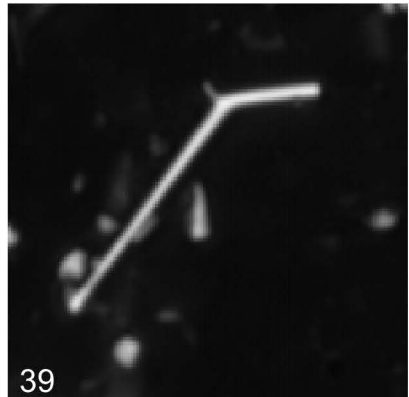
36 *Sphenolithus obtusus* 1408A-4-CC



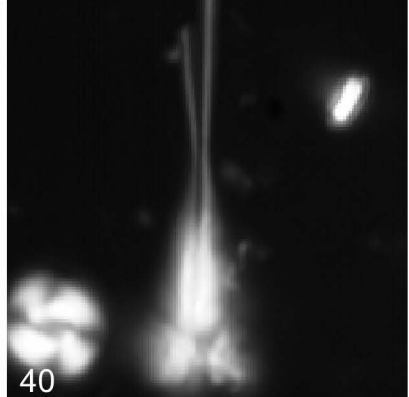
37 *Sphenolithus obtusus* 1408A-4-CC



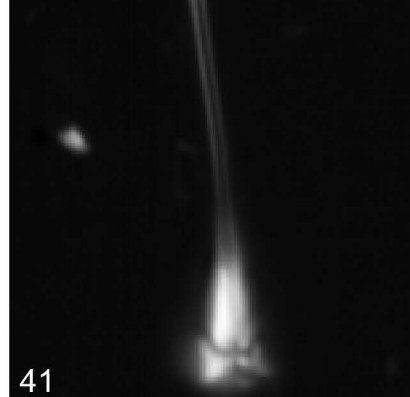
38 *Spheno. obtusus* 1408A-4-CC



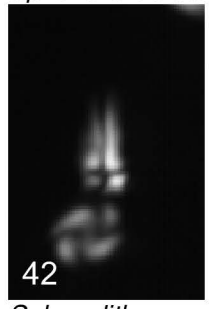
39 *sphenolith spines* 1408C-10-3, 63



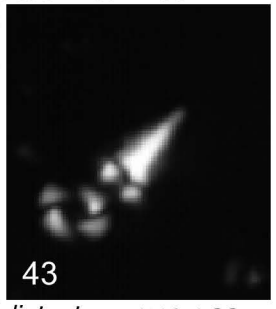
40 *Spheno. obtusus* 1408A-4-CC



41 *Spheno. obtusus* 1408A-4-CC



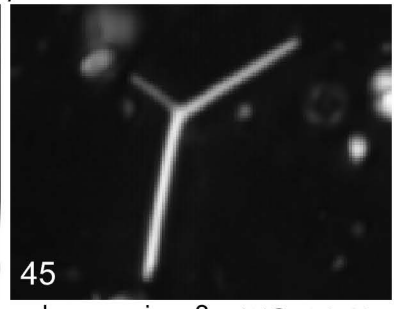
42 *Sphenolithus predistentus* 1408A-4-CC



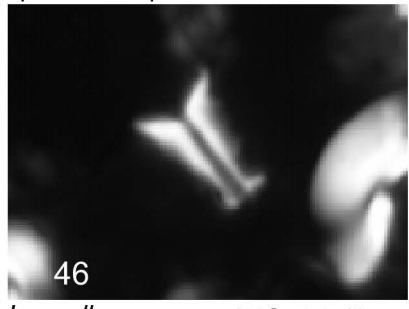
43 *spheno. spines* 1411B-27-5, 72



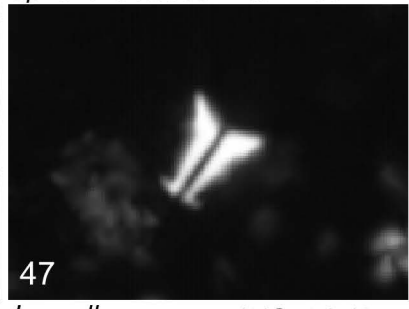
44 *spheno. spines?* 1408C-10-3, 63



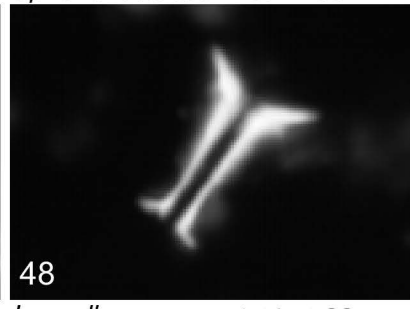
45 *spheno. spines?* 1408C-10-3, 63



46 *Leesella procera* 1408C-10-3, 63

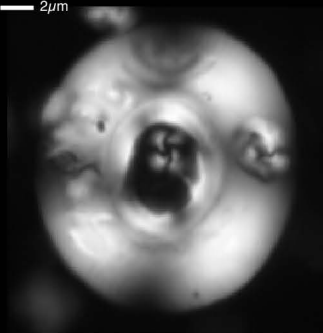


47 *Leesella procera* 1408C-10-3, 63

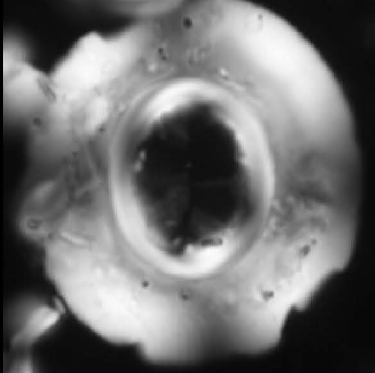


48 *Leesella procera* 1410A-10-CC

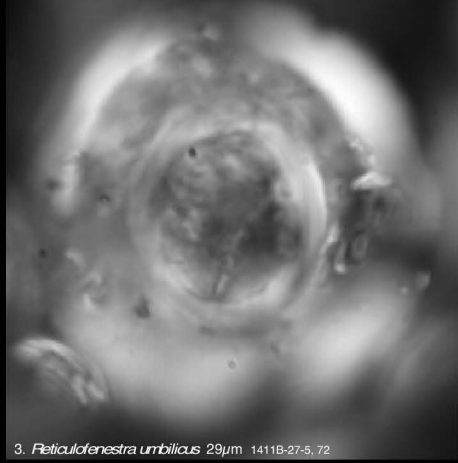
2µm



1. *Reticulofenestra umbilicus* 1409A-9-CC



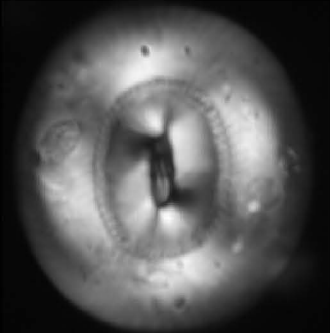
2. *Reticulofenestra umbilicus* 23µm 14011B-27-5, 23



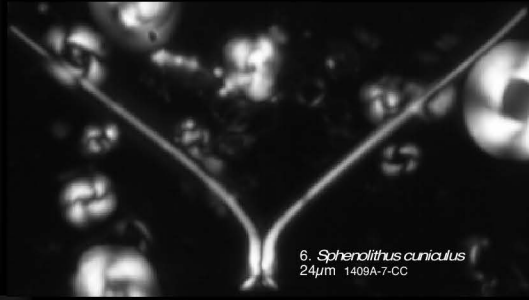
3. *Reticulofenestra umbilicus* 29µm 1411B-27-5, 72



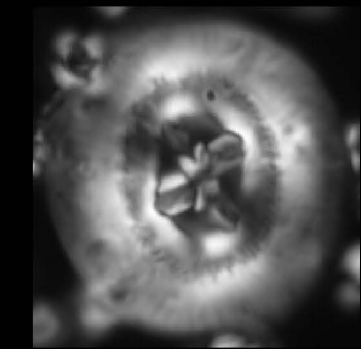
4. *Chiasmolithus grandis* 24µm 1409A-7-4, 57



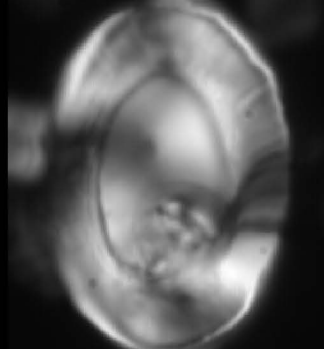
5. *Coccolithus eopelagicus* 1408A-17-4, 3



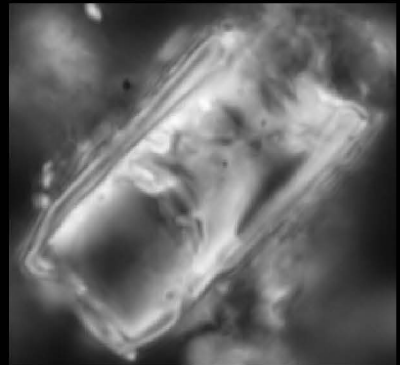
6. *Sphenolithus curvulus* 24µm 1409A-7-CC



7. *Coccolithus gigas* 1409A-9-CC



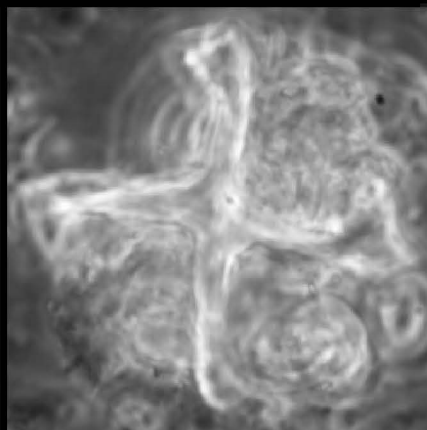
8. *Pontosphaera brinkhuisii* 1409A-7-CC



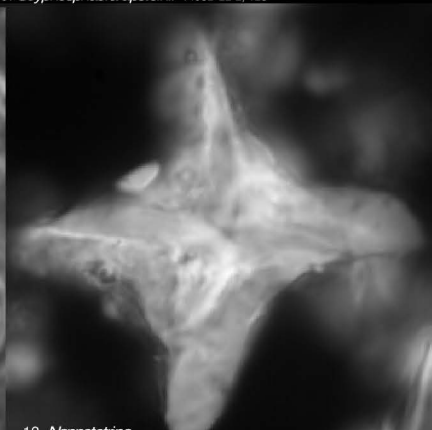
9. *Soyphosphaera apsteinii* 1408B-22-2, 123



10. *Discaster martinii* 26µm 1409A-7-CC



11. *Nannotetrina alata* 1410A-22-CC



12. *Nannotetrina fulgens* 1408A-9-CC

scale bars are 2µm



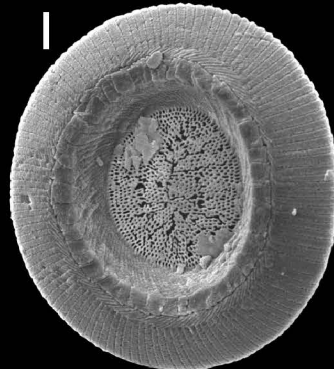
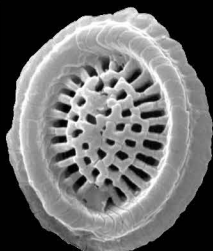
1. *Retic. minuta*
1408A-14H-5, 63cm

2. *Retic. minuta*
1408C-10H-3, 63cm

4. *Retic. minuta*
1408A-14H-5, 63cm

3. *Retic. minuta*
1409C-6H-4, 36cm

5. *Retic. sp.* 1408A-
14H-5, 63cm

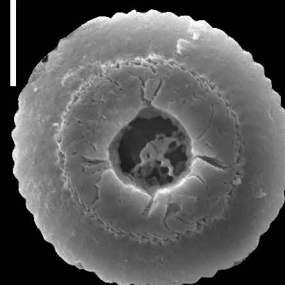
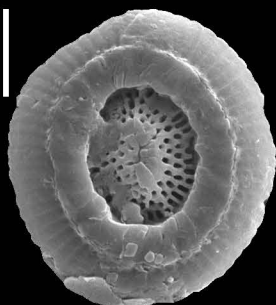


6. *Reticulofenestra macmillanii?*
1408A-14H-5, 63cm

7. *Cyclicargo floridanus*
1408A-14H-5, 63cm

8. *Reticulofenestra dictyoda*
1408A-14H-5, 63cm

9. *Reticulofenestra umbilicus*
1408C-10H-3, 63cm

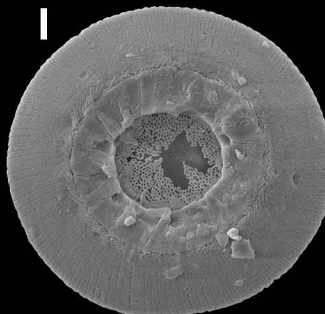
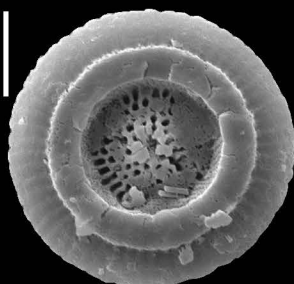


10. *Reticulofenestra lockeri*
1411B-28H-3, 105cm

11. *Reticulofenestra bisecta*
1411B-18H-2, 30cm

12. *Reticulofenestra erbae*
1411B-28H-3, 105cm

13. *Reticulofenestra reticulata*
1408B-5H-5, 63cm

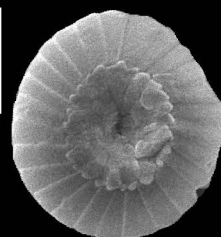
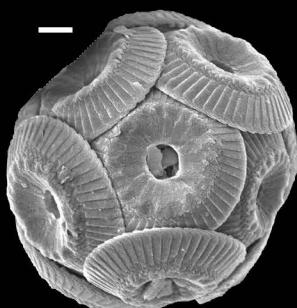


14. *Reticulofenestra reticulata*
1411B-28H-3, 105cm

15. *Reticulofenestra reticulata*
1408B-5H-5, 63cm

16. *Reticulofenestra isabellae?*
1408A-14H-5, 63cm

17. *Coccolithus pelagicus*
1408C-10H-3, 63cm



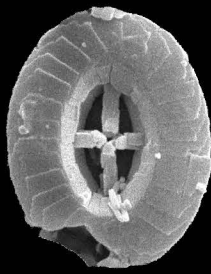
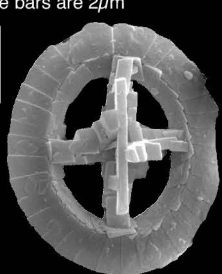
18. *Coccolithus pelagicus*
1408C-10H-3, 63cm

19. *Coccolithus formosus*
1408C-10H-3, 63cm

20. *Coccolithus formosus*
1409C-6H-4, 75cm

21. *Coccolithus pauxillus*
1408A-14H-5, 63cm

scale bars are 2µm

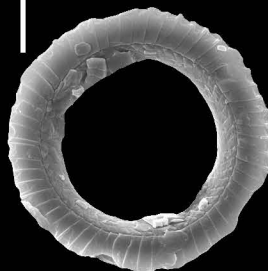


1. *Bramletteius serraculoides*
1411B-28X-3, 105cm

2. *Cruciplacolithus inseadus*
1408A-14H-5, 63cm

3. *Chiasmolithus nitidus*
1408A-14H-5, 63cm

4. *Chiasmolithus grandis* 1408A-14H-5, 63cm

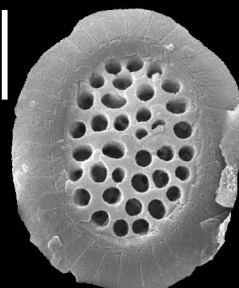
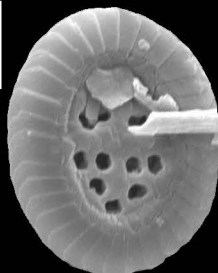


5. *Chiasmolithus grandis*
1408C-10H-3, 63cm

6. *Chiasmolithus solitus*
1408A-14H-5, 63cm

7. *Umbilicosphaera bramlettei*
1408A-14H-5, 63cm

8. *Umbilicosphaera bramlettei*
1408A-14H-5, 63cm



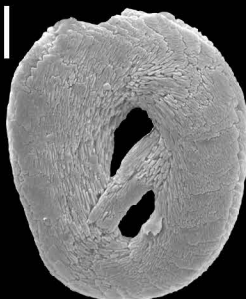
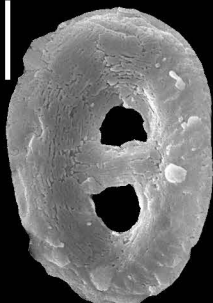
9. *Clausi*, sp. small
1408A-14H-5, 63cm

10. *Clausi*, sp. small
1409C-6H-4, 36cm

11. *Clausi subdistichus*
1408A-14H-5, 63cm

12. *Clausiococcc. subdistichus*
1408A-14H-5, 63cm

13. *Clausiococcc. fenestratus*
1408C-10H-3, 63cm



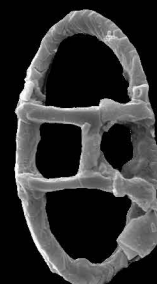
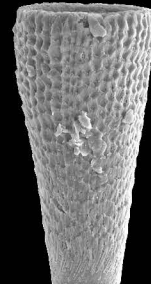
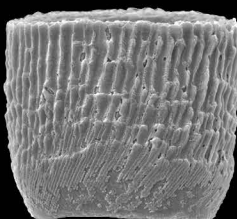
14. *Helicosph. wilcoxonii*
1411B-28X-3, 105cm

15. *Helicosph. seminulum*
1408C-10H-3, 63cm

16. *Helicosph. bramlettei*
1408C-10H-3, 63cm

17. *Helicosph. papillata*
1408B-5H-5, 63cm

18. *Helicosph. papillata?*
1408A-14H-5, 63cm



19. *Helicosph. compacta*
1408C-10H-3, 63cm

20. *Pontosphaera pulchra*
1408A-14H-5, 63cm

21. *Scyphosphaera apsteinii*
1408C-10H-3, 63cm

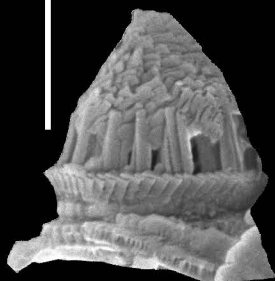
22. *Scy. expansa*
1408C-10H-3, 63cm

23. *Neococco. dubius*
1408A-14H-5, 63cm

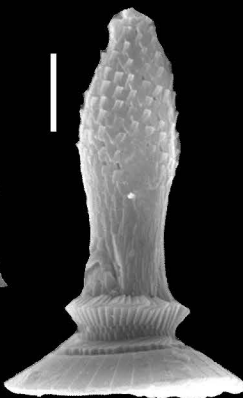
scale bars are 2µm



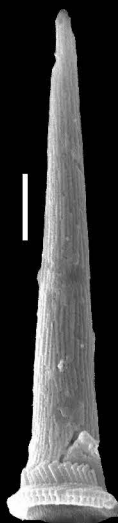
1. *Blackites deflandrei* var.
1 1408B-5H-5, 63cm



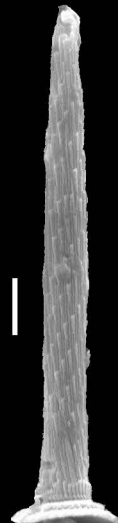
2. *Blackites deflandrei* var. 1
1408C-7H-4, 93cm



3. *Blackites gladius*
1408A-14H-5, 63cm



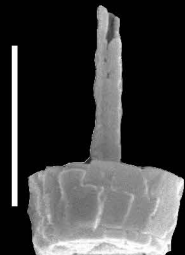
4. *B. spinosus*
1408A-22X-2, 63cm



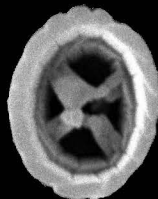
5. *B. tenuis* 1408A-
14H-5, 63cm



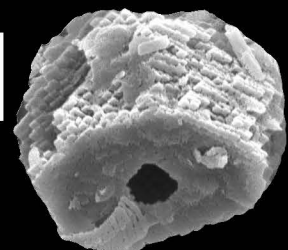
6. *B. tortilis*
1408A-14H-5,
63cm



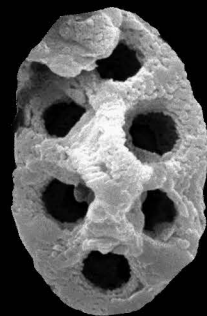
7. *Pocillithus spinulifer*
1408A-14H-5, 63cm



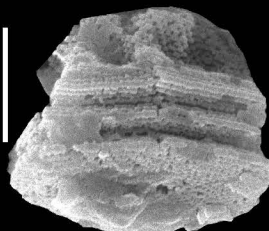
8. *Pocillithus*
spinulifer? 1408A-
14H-5, 63cm



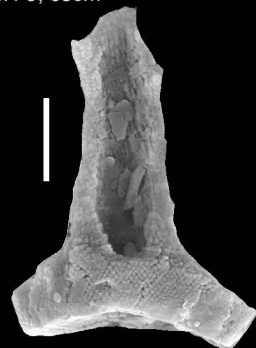
9. *Daktylethra unitatis* 1408B-
5H-5, 63cm



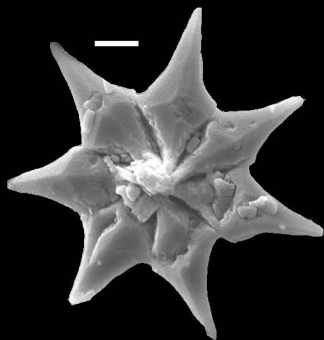
10. *Holodiscolithus solidus*
1408C-10H-5, 63cm



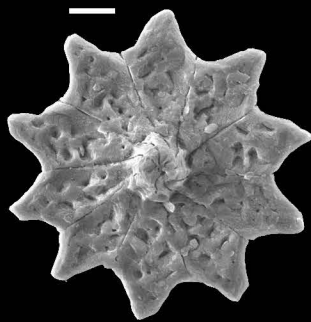
11. *Lanternithus minutus*
1408C-10H-5, 63cm



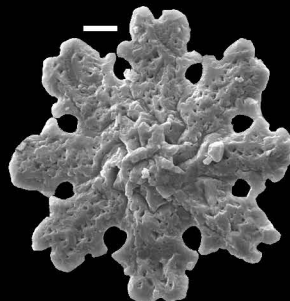
12. *Z. bijugatus* 1411B-28X-
3, 105



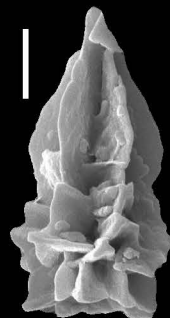
13. *Discoaster saipanensis*
1409C-6H-4, 75cm



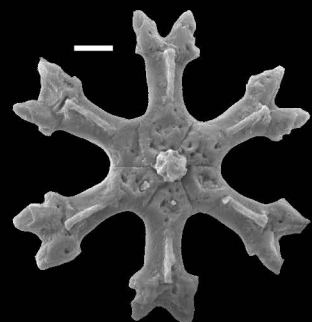
14. *Discoaster barbadiensis*.
1408C-10H-3, 63cm



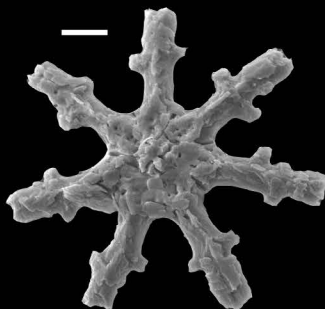
15. *Discoaster* cf. *D. nodifer*
1408A-14H-5, 63cm



16. *Sphenolithus radians*
1409C-6H-4, 75cm



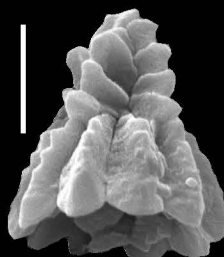
17. *Discoaster distinctus*
1408C-10H-3, 63cm



18. *Discoaster nodifer* 1408C-
10H-3, 63cm



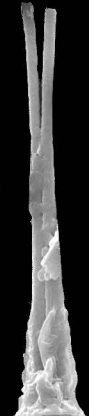
19. *Sphenolithus moriformis*
1408A-14H-5, 63cm



20. *Sph. spiniger*
1409C-6H-4, 75cm



21. *Sph. obtusus*
1408B-5H-5, 63cm



22. *Sph. strigosus*
1408A-14H-5