Paleocene calcareous nannofossils from Tanzania (TDP sites 19, 27 and 38)

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Abstract

This paper documents the nannofossil record from the oldest yet recovered Paleogene sediments – Selandian to Thanetian (Zone NP5-7) – from the Tanzania Drilling Project. These sediments include frequent horizons with exceptionally preserved nannofossils and very high diversities. The observation of this high quality preservation extends the stratigraphic record of the Tanzanian Kilwa Group microfossil lagerstätte into the Paleocene. These new records include the oldest yet stratigraphic occurrences of a number of modern coccolithophore groups – the Pontosphaeraceae (*Pontosphaera*), Rhabdosphaeraceae (*Blackites*), Syracosphaeraceae (*Syracosphaera*), Calcidiscaceae (*Calcidiscus*), *Gladiolithus* and *Solisphaera* – indicating that the majority of Cenozoic coccolithophore diversity was established during the Paleocene radiation, soon after the Cretaceous-Paleogene boundary extinctions. The frequent and consistent occurrence of the Mesozoic taxon *Zeugrhabdotus embergeri* in Zone NP5, suggests this is a second *Zeugrhabdotus* survivor species. Sixteen new species are described: *Braarudosphaera insecta*, *Bramletteius cultellus*, *Coccolithus subcirculus*, *Ericsonia aliquanta*, *Ericsonia media*, *Ericsonia monilis*, *Ericsonia orbis*, *Ellipsolithus pumex*, *Lanternithus unicavus, Pontosphaera veta*, *Solisphaera tegula, Solisphaera palmula, Toweius patellus*, *Toweius reticulum*, *Youngilithus transversipons* and *Youngilithus bipons*. Emended taxonomic definitions are proposed for *Prinsius martini* and *Prinsius bisulcus*.

Keywords Paleocene, Selandian-Thanetian, new nannofossil species, exceptional preservation

1. Introduction

The Tanzania Drilling Project first targeted Paleogene stratigraphic intervals with the principal objective of recovering sections with high sedimentation rates and exceptional calcareous microfossil preservation. These sediments contain glassy foraminifera, as required for high-quality carbonate stable isotope study, but they also yield exceptional calcareous nannofossil preservation, demonstrated by elevated diversity, conservation of small and fragile taxa, and the observation of undisturbed nannofossil concentrations on rock surfaces (e.g., Bown et al., 2008, 2009; Dunkley Jones et al., 2009). Here we report on results from the second phase of the Tanzanian Drilling Project (TDP) and show that similarly exceptional taphonomy is also present in the oldest Tanzanian Paleocene sediments yet recovered (Zones NP5-7), at TDP sites 19, 27 and 37 (Fig. 1).

2. Methodology

Samples were prepared as smear slides (Bown & Young, 1998) and analysed using a Zeiss Axiophot microscope at x1000-1250 magnification in cross polarised and phase contrast light. Assemblages were logged semi-quantitatively, and slides were observed for at least 30 minutes, in most cases much longer. The nannofossil biozones of Martini (1971) were applied. Unprocessed, broken rock surfaces were viewed using scanning electron microscopy (SEM) (Lees *et al*., 2004; Bown *et al*., 2008). The observation of rock surfaces is a particularly productive method in these hemipelagic sediments, allowing the imaging of *in situ* nannofossil concentrations on bedding or lamina surfaces that are undisturbed by large metazoan bioturbation and which conserve collapsed coccospheres and fragile taxa (Bown et al., 2008) (e.g., Pl. 10, fig. 1; Pl. 13, fig. 19).

3. Material

TDP sites 19, 27 and 37 were sited in order to recover Maastrichtian/Paleocene boundary successions, based on field surveys that had revealed closely associated Paleocene limestones and upper Maastrichtian mudstones (Nicholas et al., 2006). Initial results, including preliminary biostratigraphy based on nannofossils and planktonic foraminifera, are published in Nicholas et al. (2006) and Jiménez Berrocoso et al. (2012; 2015).

TDP Site 19 was drilled by the road to Pande, between Hotelitatu and Mkazambo (UTM 37L 550743, 8973063) (Fig. 1), and recovered 42 m of dark greenish grey claystones and silty claystones (Nicholas et al., 2006). TDP sites 27 and 37 were located on top of Kimamba Hill, 19.7 km west of Kilwa Masoko (UTM 37L 536532, 9013949), and both recovered similar Paleocene/Maastrichtian successions (Jiménez Berrocoso et al., 2012; 2015) (Fig. 1). At TDP Site 27, core recovery was poor in the upper portion of the borehole and drilling terminated in unconsolidated sands at 18.40 m, with Paleocene, but no Cretaceous, sediment cored. At TDP Site 37, coring recovered a similar upper section but succeeded in recovering the underlying Cretaceous sediments. At both sites the middle Paleocene section comprises limestones, calcareous sandstones and occasional soft, claystone interbeds. The upper sections at both sites (Cores 1 through 6) contain bioclasts of red and green algae indicating re-deposition of shallow water carbonates. Biotic components in the cores below this suggest a deepening of the depositional environment and the nannofossiliferous samples predominantly come from the claystones of this interval. TDP Site 37 encountered limestone breccias in cores TDP37/11 and 12 and below this, a thick succession of Maastrichtian olive gray, calcareous claystones (Jiménez Berrocoso et al., 2012; 2015). In general, these sediments are thought to have been deposited in an outer shelf-upper slope setting (Nicholas et al., 2006; Jiménez Berrocoso et al., 2012; 2015).

4. Results and discussion

One of the objectives of the second phase of the TDP was the recovery of Cretaceous/Paleogene (K/Pg) boundary sections in the Kilwa Group microfossil lagerstätte succession. TDP sites 27 and 37 were drilled near to outcrop sections that have yielded early Paleocene and late Maastrichtian aged microfossils, but coring has revealed that the boundary interval is missing in a hiatus representing around 8 million years (Jiménez Berrocoso et al., 2015). However, the middle Paleocene sediments lying above the hiatus contain exceptionally well-preserved calcareous microfossils, and nannofossil assemblages that include a number of unusual features.

4.1 Nannofossil biostratigraphy and preservation

TDP sites 27 and 37 cored comparable sedimentary successions that included sandy and silty intervals with rare or no nannofossils. However, clay-rich levels contain common to abundant nannofossils with exceptionally good preservation (Charts 1 and 2). TDP Site 19 recovered sediments with good to exceptionally well-preserved nannofossils present throughout (Chart 3).

The quality of nannofossil preservation is evident from light microscope viewing and, in particular, through the presence of abundant small coccoliths (*Prinsius* and *Toweius*), conspicuous fragile taxa (holococcoliths and *Calciosolenia*) and the presence of well-preserved larger taxa that are nevertheless sensitive to preservation, in this case, notably, *Ellipsolithus* and *Pontosphaera*. The assemblages are also unusually diverse and in the Zone NP5 interval, yield species richness values up to 70 species with ~100 species present in total (Charts 1 and 2). The Zones NP6-7 interval yields species richness up to 74 species with ~130 species present in total (Chart 3). These values are higher than the global compilation estimates of Bown et al. (2004).

TDP Site 27. Of the seventeen samples studied, six were barren and six contained only sparse assemblages (Chart 1). Cores 27/5 through 27/7 yielded common to abundant and exceptionally well preserved nannofossils. The presence of *Ellipsolithus macellus* and absence of *Heliolithus kleinpelli* or discoasters indicates an age equivalent to nannofossil zones NP4 or NP5. Although *Fasciculithus* are rare, the presence of forms that resemble *F. tympaniformis* and taxa that characterise the Selandian fasciculith radiation (e.g., Varol, 1998; Bernaola et al., 2009) suggests a position close to the NP4/5 zonal boundary (Note that some of these taxa have recently been described within the new genera *Diantholitha* and *Lithoptychius* by Aubry et al., 2011 and Monechi et al., 2013). This age determination is further supported by the presence of *Sphenolithus, Toweius eminens* and *Neochiastozygus perfectus* (e.g., Varol, 1998; Bernaola et al., 2009). Age diagnostic assemblages were not recovered in the other cores. The assemblages recovered at TDP Site 27 are closely comparable to those recovered in the Paleocene interval at TDP Site 37 (Jiménez Berrocoso et al., 2012) but may come from slightly higher in Zone NP5, as samples contain rare *Heliolithus cantabriae* but lack *Fasciculithus pileatus*.

TDP Site 37. Of the thirteen samples studied, two were barren (cores 37/1 and 37/4) and three contained only very sparse assemblages (cores 37/2 and 37/3). Cores 37/6 through 11 generally yielded common to abundant and exceptionally well preserved nannofossils (Chart 2). In cores TDP37/11 through 6 the presence of *Ellipsolithus macellus, Fasciculithus janii, F. pileatus* and the absence of *Heliolithus kleinpellii* or discoasters indicate an age equivalent to nannofossil Zones NP4-5 (Selandian). The presence of several questionable specimens attributable to *Fasciculithus tympaniformis* suggests a position close to the NP4/5 zonal boundary. This age determination is further supported by the presence of *Sphenolithus, Toweius eminens, Neochiastozygus perfectus* and *Fasciculithus* spp. typical of the Selandian fasciculith radiation, including *F. janii*, *F. pileatus*, *F. ulii* and forms recently described as *Lithoptychius* (e.g., Aubry et al., 2011; Monechi et al., 2013).

Other stratigraphically distinctive components include the *Ericsonia* species, *E. subpertusa* and *E. aliquanta* sp. nov., and diverse *Cruciplacolithus* (including *C. tenuis*), and *Neochiastozygus* (especially common *N. modestus*).

TDP Site 19. Nineteen samples were studied of which one was barren (core 19/4) and one contained only very sparse nannofossils (core 19/16). The majority of samples yielded nannofossils that are frequent to abundant and good to exceptionally well preserved (Chart 3).

Heliolithus kleinpellii is present in the lowest sample indicating an age equivalent to Zone NP6 (Selandian/Thanetian boundary interval), and *Discoaster mohleri* is present from Core 15 indicating an age equivalent to Zone NP7. Other stratigraphically distinctive components include *Bomolithus* spp. and diverse *Ericsonia*, *Cruciplacolithus* (including *C. frequens*) and *Neochiastozygus*. Holococcoliths are unusually diverse for sediments of this age and include *Clathrolithus ellipticus*, *Holodiscolithus* spp., *Lanternithus* spp., *Semihololithus* spp. and *Zygrhablithus bijugatus*.

4.2 Assemblage composition

TDP Site 27 and 37. The assemblages at both older Paleocene sites are dominated by abundant to common *Prinsius, Toweius, Coccolithus, Neochiastozygus, Ericsonia, Umbilicosphaera jordanii* and *Zeugrhabdotus sigmoides*. *Ellipsolithus* coccoliths are also frequent to common and diverse. Most samples also contain rare reworked late Cretaceous nannofossils (e.g., *Micula, Eiffellithus, Watznaueria* and *Retecapsa*).

Of particular significance are the presence of *Pontosphaera* spp. and *Gladiolithus*, as these represent the earliest occurrences, so far recorded (Zone NP5), of these important extant coccolithophore groups. *Pontosphaera* spp. (and the family Pontosphaeraceae) and *Gladiolithus* have not previously been found in rocks older than latest Paleocene (Zone NP9, e.g. Bybell and Self-Trail, 1995; Bown, 2010).

The Mesozoic taxon *Zeugrhabdotus embergeri* is also found frequently and consistently at stratigraphic levels far above (Zone NP5) it's previously documented extinction level at the K/Pg boundary, within assemblages that are typically lacking in significant Cretaceous reworking. It is therefore most likely a second *Zeugrhabdotus* survivor species, alongside *Z. sigmoides*.

The presence of small, early variants of *Neococcolithes protenus* and early occurrences of *Calciosolenia aperta* in Zone NP5 are also notable.

TDP Site 19. The assemblages at TDP Site 19 are dominated by *Coccolithus pelagicus*, *Toweius pertusus* and *U. jordanii*, along with frequent to common *Campylosphaera dela*, *Toweius eminens*, *Calciosolenia aperta* and *Braraudosphaera* spp., and frequent *Ellipsolithus*, *Ericsonia*, *Fasciculithus*, *Neochiastozygus*, *Sphenolithus*, *Zeugrhabdotus sigmoides*, *Zygodiscus* spp. and *Zygrhablithus bijugatus*.

Of particular significance are the presence of *Blackites* (in LM and SEM) and *Syracosphaera* (in SEM), as these represent the earliest occurrences so far recorded (Zones NP7 and NP6, respectively) of these important extant coccolithophore groups. SEM observations of *Calcidiscus* sp. and *Hayaster perplexus* also represent the earliest recorded occurrences of these genera (see also Bown et al., 2007).

The presence of *Campylosphaera dela* in sediments of this age is not unprecedented, but the origination time of this species is often reported to be considerably younger, e.g., defining a subzone within uppermost Paleocene Zone NP9 (Bukry, 1973; see discussion in Bown, 2005). The occurrence of *Z. bijugatus*, *Ellipsolithus anadoluensis* and *Lophodolithus nascens* are amongst the oldest documented records for these particular species.

4.3 Significance of extended stratigraphic ranges

All of these unusually early occurrences can be explained by the enhanced preservation of the calcareous microfossils in these Tanzanian sediments. This has facilitated the preservation of the particularly small and/or fragile coccoliths that characterise these particular coccolithophore groups, e.g., *Blackites*, *Syracosphaera*, *Gladiolithus*, and also the small and more fragile coccoliths that occur in the early history of many lineages prior to size increases which improve preservation potential, e.g., *Ellipsolithus*, *Pontosphaera*, *Zygrhablithus*, *Neococcolithes* and *Campylosphaera*.

The Order Syracosphaerales is the most diverse modern coccolithophore group but is poorly represented in the fossil record due to typically small and fragile coccoliths. The presence of *Algirosphaera*-like *Blackites* coccoliths (see taxonomy section) and *Syracosphaera* in the late Paleocene sediments of TDP Site 19 suggests that the Rhabdosphaeraceae and Syracosphaeraceae originated early in the Cenozoic, during the Paleocene diversification.

Gladiolithus is one of very few modern lower photic zone adapted groups and their presence in the Paleocene sediments at TDP Site 27 (Sample 27/7-1, 6 – Zone NP5) indicates that they originated early in the Cenozoic, during the post-K/Pg boundary Paleocene diversification. The observation of *Solisphaera* like coccoliths in the same samples suggests that a relatively diverse, specialized lower photic zone coccolithophore assemblage was already established at this time.

The extension of stratigraphic ranges for five major taxonomic groups (Calcidiscaceae, Pontosphaeraceae, Rhabdosphaeraceae, Syracosphaeraceae and *Gladiolithus*) indicates that the majority of Cenozoic diversity was established in the Paleocene. Of the 10 fossil forming Cenozoic coccolithophore families (Calcidiscaceae, Calciosoleniaceae, Coccolithaceae, Helicosphaeraceae, Noelaerhabdaceae, Pontosphaeraceae, Prinsiaceae, Rhabdosphaeraceae, Syracosphaeraceae and Zygodiscaceae) all but the Helicosphaeraceae and Noelaerhabdaceae are represented in these Paleocene Tanzanian sediments.

5. Systematic palaeontology

The aim of this section is to provide images of the notable nannofossils from the Paleocene TDP sites 19, 27 and 37, and to describe the 16 new taxa. The majority of observed taxa are listed but descriptions and remarks are only provided where new information is pertinent. The descriptive terminology (including size classes) follows the guidelines of Young *et al.* (1997). The higher taxonomy essentially 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 and the meaning is given in each case. Range information is given for stratigraphic distributions in the Tanzanian sites. Morphometric data are given for all new taxa based on measurements from a representative range of specimens. 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.

5.1 The Plates

The nannofossil taxa from TDP 19, 27 and 37 are illustrated in Plates 1-13. The SEM images are reproduced at variable magnifications but a 1µm scale bar is provided beside each image, unless otherwise noted. The LM images are reproduced at constant magnification and a 2µm scale bar is provided beside at least one of the images on each plate. The sample information is provided using the following notation: Core (3 m lengths)-Section (1 m subdivisions of each core), depth in Section in cm, e.g. 19/4-1, 60 cm is TDP Site 19, Core 4, Section 1 at a depth of 60 cm and represents a subsurface depth of 9.6 m (see Pearson *et al*., 2004 for details of drilling methods).

PLACOLITH COCCOLITHS

Order ISOCHRYSIDALES **Pascher, 1910**

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

Genus *Prinsius* Hay & Mohler, 1967

Prinsius bisulcus (Stradner, 1963) Hay & Mohler, 1967 emend.

Pl. 1, figs 3-5. **Description**: Medium sized (maximum length >5.5 µm), elliptical, bicyclic placolith with bright central area characterised by two dark areas or grooves along the longitudinal axis at each end. **Remarks**: Similar to *Prinsius martinii* but based on a detailed biometric study Wei and Liu (1992) suggested that *P. martinii* should be distinguished from *P. bisulcus* based on coccolith length, using <5.0 µm for *P. martinii* or >5.0 µm for *P. bisulcus*. However, the holotype of *P. martinii* is 5.5. µm and the type range given for *P. bisulcus* is 4.0-6.5 µm, with the holotype drawing ~6.5µm. The distinguishing limit between these two taxa has been raised here to 5.5 µm, to account for the holotype of *P. martinii.*

Prinsius martinii (Perch-Nielsen, 1969) Haq, 1971 emend.

Pl. 1, figs 1-2. **Emended diagnosis**: Small, elliptical, *Prinsius* coccolith with very narrow to closed central area; maximum length 5.5 µm or less.

Genus *Towieus* Hay & Mohler, 1967

Toweius eminens (Bramlette & Sullivan, 1961) Perch-Nielsen, 1971 Pl. 1, figs 9-11

Toweius pertusus (Sullivan, 1965) Romein, 1979 Pl. 1, figs 7-8; Pl. 10, fig. 6

Toweius patellus sp. nov.

Pl. 1, fig. 12. **Derivation of name**: From *patella*, meaning 'plate', referring to the appearance of the plate-like central area structure that is diagnostic of this species. **Diagnosis**: Medium sized, broadly elliptical to subcircular *Toweius* with relatively wide central area (width similar to or slightly greater than the rim) spanned by weakly birefringent plate; no obvious perforations are apparent in LM. **Differentiation:** Distinguished from other *Toweius* by the relatively wide central area spanned by a plate with no clearly visible perforations in LM. **Dimensions**: L = 5.0µm.

Holotype: Pl. 1, fig. 12. **Paratypes**: Bown (2005, *JNR* 27), Pl. 1, fig. 30. **Type locality**: TDP Site 27, Kimamba Hill, Kilwa, Tanzania. **Type level**: Middle Paleocene (Selandian), Sample TDP27/7-1, 46 cm (Zone NP5). **Occurrence**: Zones NP5-11; TDP Sites 3, 7, 14, 16, 27 and 37.

Toweius reticulum sp. nov.

Pl. 10, figs 1-3, 5. **Derivation of name**: From *reticulum*, meaning 'little net', referring to the reticulate central area structure of this species. **Diagnosis**: Very small *Toweius* (1.8-3.0 µm) with relatively wide central area (width similar to or slightly greater than the rim) spanned by a grill formed from radial bars that merge to form a central longitudinal bar or plate, which may be perforate. **Remarks**: This species has not been unambiguously identified in LM due to its small size, but is likely one of the taxa commonly informally grouped as small *Toweius*. **Differentiation:** Distinguished from other *Toweius* by the small size and central area grill predominantly composed of radial, lath-like bars. Somewhat similar to Eocene specimens described as *Cyathosphaera martinii* Hay and Towe, 1962, but *T. reticulum* has thicker central area bars and a central longitudinal structure with pores. In addition, the generic affinity of *C. martini* is uncertain and it may be a small reticulofenestrid. **Dimensions**: L = 2.5µm. **Holotype**: Pl. 10, fig. 1. **Paratypes**: Pl. 10, fig. 3; Pl. 10, fig. 5. **Type locality**: TDP Site 19, Pande, Tanzania. **Type level**: Upper Paleocene, Sample TDP19/26-1, 25 cm (Zone NP6). **Occurrence**: Zone NP6; TDP Site 19.

Toweius tovae Perch-Nielsen, 1971 Pl. 1, figs 13-18; Pl. 10, fig. 4

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

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

Pl. 1, figs 19-51; Pl. 2, figs 1-27. **Remarks:** Lower and Middle (Danian-Selandian) Paleocene assemblages contain diverse coccolithacean coccoliths including typical *Coccolithus*-like forms (elliptical *C. pelagicus* to subcircular/circular *C. foraminis* and *C. subcirculus*) together with forms that have broader upper-tube-element cycles that dominate the distal shield, resulting in a bright LM XPL image. These latter forms are included here in *Ericsonia*.

Genus *Coccolithus* Schwartz 1894

Coccolithus foraminis Bown, 2005

Pl. 1, figs 21-24. **Description**: Subcircular with wide central area (similar in width to the rim).

Coccolithus latus Bown, 2005

Pl. 1, figs 25-26; **Description**: Broadly elliptical with wide central area (typically wider than the rim).

Coccolithus pelagicus (Wallich, 1877) Schiller, 1930

Pl. 1, figs 19-20; Pl. 10, figs 7-8. **Remarks**: Includes forms with relatively broad transverse bars.

Coccolithus subcirculus sp. nov.

Pl. 1, figs 27-30. **Derivation of name**: From *sub*, meaning 'close to', and *circulus*, meaning 'circular', referring to the subcircular outline of this species. **Diagnosis**: Small to medium-sized *Coccolithus* with subcircular to circular outline and narrow, central area (less than the width of the rim). **Remarks**: The first appearance of the circular species *Coccolithus formosus* is typically cited as lower Eocene, but similar, near-circular coccoliths of *Coccolithus* are found in this study from Zone NP5 and are described as a new species. **Differentiation**: Distinguished from *Coccolithus formosus* (see Eocene specimens from TDP Site 2 shown in Pl. 2, figs 31-32) by its typically subcircular outline and older stratigraphic range (*Coccolithus formosus* ranges from the lower Eocene to lower Oligocene). Distinguised from *Coccolithus foraminis* by its narrower central area. **Holotype dimensions**: L = 5.7µm. **Holotype**: Pl. 1, fig. 30. **Paratype**: Pl. 1, fig. 28. **Type locality**: TDP Site 27, Kimamba Hill, Kilwa, Tanzania. **Type level**: Middle Paleocene (Selandian), Sample TDP27/7-1, 6 cm (Zone NP5). **Occurrence**: Zone NP5; TDP Sites 27 and 37.

Genus *Ericsonia* Black, 1964

Pl. 1, figs 31-51; Pl. 2, figs 1-27. **Description**: Typically subcircular to circular coccolithacean coccoliths with a broad upper-tube cycle that is just narrower than the shield width and so dominates the LM XPL image, resulting in a moderately bright appearance. A range of central area widths are seen - from narrower than the rim width to equal to or slightly broader than the rim width - and the central area is usually vacant or, more rarely, spanned by bars (e.g., *E. staerkeri*). SEM images of *Ericsonia* coccoliths (e.g., Perch-Nielsen, 1977, Pl. 16, figs 2, 11; Bown, 2010, Pl. 2, fig. 14; and herein Pl. 11, figs 4-7) show a narrow distal shield cycle with steep outward slope and a broad upper-tube cycle formed from numerous clockwise imbricating elements with strong laevogyre curvature. This is distinct from *Coccolithus pelagicus* ultrastructure, where the distal shield cycle is relatively broad and shallowly sloping. **Remarks:** The name *Ericsonia* has been applied to a wide range of circular and elliptical placoliths, many of which are now best classified within other general, such as, *Calcidiscus* (e.g, *detecta*), *Clausicoccus* (e.g, *subdisticha, fenestrata*), *Hughesius* (e.g, *tasmaniae*) and *Coccolithus* (e.g, *formosa*). As defined here *Ericsonia* species are mainly restricted to the Paleocene. Although most *Ericsonia* coccoliths are relatively distinct from those of *Coccolithus*, a number of forms share features of both groups and are included within the new species *Ericsonia media* here (Pl. 1, figs 31-43). The species included in *Ericsonia* are as follows:

- *E. aliquanta* sp. nov. - medium-sized (5-9µm), circular to subcircular with relatively wide central area;
- *E. media* sp. nov. - medium to large (~6-11µm), subcircular to circular with a moderately broad upper-tube cycle and narrow central area;
- *E. monolis* sp. nov. - very small (~3µm), circular with raised distal collar and tall proximal shield;
- *E. orbis* sp. nov. – small (<5µm), circular with relatively wide central area;
- *E. robusta* – large (>9µm), circular with wide central area;
- *E. staerkeri* - small (<5µm), circular with relatively wide central area spanned by cross bars;
- *E. subpertusa* – medium to large, subcircular to circular with narrow central area.

Occurrence: Common in Paleocene assemblages, becoming rare in the upper Paleocene. The large species, *E. robusta*, has a last occurrence within Zone NP9 (Raffi et al., 2005). The small and inconspicuous species, *E. orbis* sp. nov., continues into the Eocene, but it is rare, sporadically distributed and rarely documented. The extinction level for the genus is therefore difficult to determine, but may be close to the Eocene/Oligocene boundary.

Ericsonia aliquanta sp. nov.

Pl. 1, fig. 51; Pl. 2, figs 1-11. **Derivation of name**: From *aliquantus*, meaning 'of some size, moderate', referring to the intermediate size of this species, relative to *E. orbis* and *E. robusta*. **Diagnosis**: Medium-sized (5-9µm), circular to subcircular *Ericsonia* coccoliths with a central area width similar to or greater than the rim width. **Differentiation**: Distinguished from *Ericsonia robusta* by its smaller size, from *Ericsonia orbis* by its larger size and from *Ericsonia subpertusa* by its relatively wider central area. Previous work most likely included these forms in *E. robusta*. **Holotype dimensions**: L = 7.1µm. **Holotype**: Pl. 2, fig. 5. **Paratype**: Pl. 2, figs 1-4. **Type locality**: TDP Site 27, Kimamba Hill, Kilwa, Tanzania. **Type level**: Middle Paleocene (Selandian), Sample TDP27/7-1, 46 cm (Zone NP5). **Occurrence**: Zones NP5-9; TDP Sites 10, 27 and 37.

Ericsonia orbis sp. nov.

Pl. 1, figs 44-50; Pl. 11, figs 4-6. **Derivation of name**: From *orbis*, meaning 'circle or ring', referring to the general morphology of this species. **Diagnosis**: Small (<5µm), circular *Ericsonia* coccoliths with a central area width similar to, or just slightly greater than, the rim width. **Differentiation**: Distinguished from *Ericsonia robusta* and *Ericsonia aliquanta* by its smaller size, and from *Ericsonia subpertusa* by its smaller size and relatively wider central area. Probably largely overlooked in previous work or considered to be small *E. robusta*. **Holotype dimensions**: L = 3.6µm. **Holotype**: Pl. 1, fig. 45. **Paratype**: Pl. 1, fig. 49. **Type locality**: TDP Site 27, Kimamba Hill, Kilwa, Tanzania. **Type level**: Middle Paleocene (Selandian), Sample TDP27/7-1, 6 cm (Zone NP5). **Occurrence**: Zone NP5; TDP Sites 27 and 37. **Range:** Zones NP5-NP21?

Ericsonia media sp. nov.

Pl. 1, figs 33-43. **Derivation of name**: From *medius*, meaning 'intermediate', referring to the morphology of this species, which shares features seen in both *Ericsonia* and *Coccolithus* coccoliths. **Diagnosis**: Medium to large, subcircular to circular *Ericsonia* with a moderately broad upper-tube cycle and central area that is less than the rim width. **Differentiation**: In XPL, the upper-tube cycle appears to be narrower than that seen in typical *Ericsonia* coccoliths and broader than that seen in *C. pelagicus*. The outer edge of the upper-tube cycle shows a distinct beaded appearance at certain focus points. **Holotype dimensions**: L = 6.4µm (range 6.0-10.4µm). **Holotype**: Pl. 1, fig. 35. **Paratype**: Pl. 1, fig. 40. **Type locality**: TDP Site 19, Pande, Tanzania. **Type level**: Upper Paleocene, Sample TDP19/13-1, 36 cm (Zone NP7). **Occurrence**: Zone NP5-7; TDP Sites 19, 27 and 37.

Ericsonia monilis sp. nov.

Pl. 11, figs 1-3. **Derivation of name**: From *monilis*, meaning 'collar', referring to the collar-like structure on the distal shield of this species. **Diagnosis**: Very small, circular coccolith with *Ericsonia*-like structure, but the distal shield elements form a distinct raised collar, the inner tube cycle is in a depression around the open central area and the proximal shield appears to be narrow and relatively tall. **Remarks:** The central area width is similar to that of the rim width. The species has been observed on rock surfaces in SEM, including concentrations that likely represent collapsed coccospheres. **Dimensions**: L = ~3µm. **Holotype**: Pl. 11, fig. 2. **Paratype**: Pl. 11, fig. 1.

Type locality: TDP Site 27, Kimamba Hill, Kilwa, Tanzania. **Type level**: Middle Paleocene (Selandian), Sample TDP27/7-1, 6 cm (Zone NP5). **Occurrence**: Zone NP5; TDP Sites 27.

Ericsonia robusta (Bramlette & Sullivan, 1961) Wind & Wise in Wise & Wind, 1977

Pl. 2, figs 12-14 (specimens from TDP Site 10). **Description**: Large (>9.0 µm) circular *Ericsonia* coccoliths with narrow shields and relatively wide vacant central area (width typically greater than the rim). **Remarks**: Originally described as large (9-15µm) circular coccoliths with wide central area. The >9µm size limit allows this taxon to be distinguished from the smaller forms that are common through the Paleocene and rare through the Eocene (*Ericsonia orbis*). So defined, *E. robusta* has a restricted stratigraphic range in the upper Paleocene (e.g., Raffi et al., 2005; Agnini et al., 2007). **Range**: Upper Paleocene (Zone NP8?-lower NP9).

Ericsonia subpertusa Hay & Mohler, 1967

Pl. 2, figs 15-27; Pl. 11, fig. 7. **Description**: Subcircular to circular *Ericsonia* with relatively narrow, vacant, central area, usually narrower than the rim. Originally described as having a 'large' central opening (i.e., ~1/3 the diameter of the coccolith) but the paratypes also show specimens with narrower central areas. **Differentiation**: Distinguished from *E. robusta, E. aliquanta* and *E. orbis* by its broader rim and relatively narrower central area (~equal to the width of the rim or less).
Range: Zones NP3 to NP9.

Genus *Bramletteius* Gartner, 1969

Bramletteius cultellus sp. nov.

Pl. 2, figs 28-33. **Derivation of name**: From *cultellus*, meaning 'little knife', referring to the narrow, blade-like spine of this species. **Diagnosis**: Placolith coccoliths with long, flat, narrow, blade-like spine. **Differentiation and remarks**: Distinguished from *Bramletteius serraculoides* by its narrower spine. It is also considerably older than previously described species in this genus, which have middle Eocene to Oligocene stratigraphic ranges. This suggests that blade-like spines might not be particularly useful characters when defining genera and it is likely that *Cruciplacolithus*-like coccoliths may have produced such spines at various times during the Paleogene. The generic assignment is retained here until further stratigraphic information comes to light. **Holotype dimensions**: coccolith L = 5.4µm; spine height 7.4µm. **Holotype**: Pl. 2, fig. 28. **Paratype**: Pl. 2, fig. 32. **Type locality**: TDP Site 37, Kimamba Hill, Kilwa, Tanzania. **Type level**: Middle Paleocene (Selandian), Sample TDP37/10-1, 70 cm (Zone NP5). **Occurrence**: Zone NP5; TDP Sites 27 and 37.

Genus *Chiasmolithus* Hay et al., 1966

Chiasmolithus bidens (Bramlette & Sullivan, 1961) Hay & Mohler, 1967 Pl. 3, fig. 25

Chiasmolithus californicus (Sullivan, 1964) Hay & Mohler, 1967 Pl. 3, figs 14-16, 19

Chiasmolithus consuetus (Bramlette & Sullivan, 1961) Hay & Mohler, 1967 Pl. 3, fig. 17-18

Chiasmolithus danicus (Brotzen, 1959) Hay & Mohler, 1967 Pl. 3, figs 11-13

Chiasmolithus nitidus Perch-Nielsen, 1971 Pl. 3, figs 20-24

Genus *Campylosphaera* Kamptner, 1963

Campylosphaera dela (Bramlette & Sullivan, 1961) Hay & Mohler, 1967 Pl. 2, figs 34-35

Genus *Cruciplacolithus* Hay & Mohler in Hay et al. 1967

Cruciplacolithus edwardsii Romein, 1979 Pl. 3, figs 9-10

Cruciplacolithus frequens (Perch-Nielsen, 1977) Romein, 1979 Pl. 2, figs 46-50

Cruciplacolithus inseadus Perch-Nielsen, 1969 Pl. 10, fig. 12

Cruciplacolithus intermedius van Heck & Prins, 1987 Pl. 2, figs 37-39

Cruciplacolithus latipons Romein, 1979

Pl. 2, fig. 51; Pl. 3, figs 3-6; Pl. 10, figs 9-11 **Remarks:** *Cruciplacolithus* with central area filled by broad axial cross bars. SEM images show the central area filled by a plate-like structure (Pl. 10, figs 9-11). Subcircular and large forms are termed *C.* cf. *C. latipons* herein.

Cruciplacolithus cf. *C. latipons* Romein, 1979 Pl. 3, fig. 1-2, 7-8

Cruciplacolithus primus Perch-Nielsen, 1977 Pl. 2, fig. 36

Cruciplacolithus subrotundus Perch-Nielsen, 1969

Pl. 2, figs 40-41. **Remarks:** The specimen figured has a narrower rim and wider central area than the holotype but is similar to the specimen figured by Perch-Nielsen (1977, Pl. 50, fig. 1).

Cruciplacolithus tenuis (Stradner, 1961) Hay and Mohler in Hay et al., 1967 Pl. 2, figs 42-45

Genus *Craticullithus* Bown, 2010

Craticullithus cassus (Bown, 2005) Bown, 2010 Pl. 3, figs 26-28; Pl. 11, fig. 13

Craticullithus lamina Bown, 2010 Pl. 3, figs 31-35

Craticullithus sp. Pl. 3, figs 29-30

Genus *Clausicoccus* Prins, 1979

Clausicoccus? sp.

Pl. 3, fig. 36-38. **Remarks**: Very small (2-3 µm) placoliths with coccolithacean rim and narrow central area spanned by a four-part plate. These occurrences (Zone NP6) are significantly older than previous records of this genus, but the identification is tentative, requiring more data and preferably SEM observation.

Family **CALCIDISCACEAE** Young & Bown, 1997

Genus *Calcidiscus* Kamptner 1950

Calcidiscus? sp.

Pl. 11, fig. 8. **Remarks**: Very small (2-3 µm), subcircular placoliths seen in SEM with *Calcidiscus*-like rim and narrow, vacant central area. These are the oldest occurrences (Zone NP6) of coccoliths that can be attributed, albeit tentatively, to the *Calcidiscus* genus (see also Bown et al., 2007). **Occurrence:** Zone NP6, TDP 19.

Genus *Hayaster* Bukry 1973

Hayaster perplexus (Bramlette & Riedel, 1954) Bukry, 1973

Pl. 11, fig. 9. **Remarks**: These are the oldest occurrences (Zone NP6) of coccoliths that can be attributed to *H. perplexus.* They are rarely recorded in the fossil record but other Paleogene occurrences are discussed in Bown *et al*. (2007). **Occurrence:** Zone NP6, TDP 19.

Genus *Umbilicosphaera* Lohmann, 1902

Umbilicosphaera bramlettei (Hay & Towe, 1962) Bown et al., 2007 Pl. 3, figs 39-42

Umbilicosphaera jordanii Bown, 2005 Pl. 3, figs 43-45; Pl. 11, fig. 11-12

Placolith coccoliths *Incertae Sedis*

Genus *Ellipsolithus* Sullivan, 1964

Pl. 3, figs 46-51; Pl. 4, figs 1-18; Pl. 12, figs 1-4. **Remarks**: The oldest representatives of *Ellipsolithus* are typically recorded from the Danian (lower Paleocene Zone NP4) but these early forms are relatively small and fragile, and are typically only found when preservation is good (e.g., Agnini et al., 2007). In the Tanzania sections, *Ellipsolithus* is well represented with frequent to common occurrences from the oldest recovered Paleocene samples (Zone NP5), where three species are present (*E. distichus*, *E. macellus* and *E. pumex* sp. nov.).

Ellipsolithus anadoluensis Varol, 1989 Pl. 3, fig. 49

Remarks: When preservation is good, this is a frequent to commonly occurring species. The oldest occurrences yet recorded are herein, within Zone NP6. **Occurrence:** NP6, TDP Site 19. **Range:** Zones NP6-11 (Tanzania); NP12 (Varol, 1989).

Ellipsolithus distichus (Bramlette & Sullivan, 1961) Sullivan, 1964 Pl. 3, figs 50-51, Pl. 4, figs 1-2

Ellipsolithus cf. *E. distichus* (Bramlette & Sullivan, 1961) Sullivan, 1964

Pl. 4, figs 3-5. **Remarks**: Like *Ellipsolithus distichus* but the central area perforations are more numerous or smaller than typical forms.

Ellipsolithus macellus (Bramlette & Sullivan, 1961) Sullivan, 1964 Pl. 3, figs 46-48

Ellipsolithus pumex sp. nov.

Pl. 4, figs 7-18; Pl. 12, figs 1-4. **Derivation of name**: From *pumex*, meaning 'porous', referring to finely perforate central area of this species. **Diagnosis**: Medium-sized *Ellipsolithus* with relatively wide central area (~width similar to the rim width) spanned by a finely perforate plate. The perforations are small and irregularly distributed, but are broadly arranged in two to three cycles. In XPL, the shields typically have grey interference colour and the tube has white interference colour. **Differentiation**: Distinguished from other *Ellipsolithus* species by the finely perforate central area plate. Most similar to the early Eocene species *Ellipsolithus aubryae* Self-Trail, 2011, which is, however, larger and has a wider central area. The Paleocene species *Ellipsolithus bollii* Perch-Nielsen, 1977 has larger pores and a longitudinal ridge. **Dimensions**: L = 9.3µm (range 6.4-9.6µm). **Holotype**: Pl. 4, fig. 16. **Paratypes**: Pl. 4, fig. 8; Pl. 4, fig. 14; Pl. 12, fig. 1. **Type locality**: TDP Site 37, Kimamba Hill, Kilwa, Tanzania. **Type level**: Middle Paleocene (Selandian), Sample TDP37/10-1, 42 cm (Zone NP5). **Occurrence**: Zone NP5; TDP Sites 27 and 37.

MUROLITH COCCOLITHS

Mesozoic survivor taxa - Eiffellithales

Order EIFFELLITHALES **Rood *et al*., 1971**

Family **CHIASTOZYGACEAE** Rood *et al*., 1973

Genus *Jakubowskia* Varol, 1989

Jakubowskia leoniae Varol, 1989 Pl. 4, figs 19-20

Genus *Neocrepidolithus* Romein, 1979

Description: Murolith (loxolith) coccoliths with broad, high rim and narrow or closed central-area, which may be spanned by bars. **Remarks**: The literature Includes a number of species that are very similar and may represent synonyms, e.g., *N. coheni*, *N. neocrassus* and *N. fossus* all have narrow to closed central areas.

Neocrepidolithus grandiculus Bown, 2005

Pl. 4, figs 21-22 **Description**: The species *Neocrepidolithus grandiculus* is used here for forms with a single visible cycle in XPL and central area of variable width.

Genus *Staurolithites* Caratini, 1963

Staurolithites primaevus Bown, 2005 Pl. 4, fig. 23

Genus *Zeugrhabdotus* Reinhardt, 1965

Zeugrhabdotus embergeri (Noël, 1958) Perch-Nielsen, 1984

Pl. 4, figs 24-26 **Remarks**: *Zeugrhabdotus sigmoides* is currently considered the only Mesozoic *Zeugrhabdotus* species to have survived the end-Cretaceous mass extinction. Here, and at other locations (pers obs.), *Zeugrhabdotus embergeri* is also found frequently and consistently at stratigraphic levels far above the extinction level (e.g., Zone NP5 herein), within assemblages that are typically lacking in significant Cretaceous reworking. It is therefore most likely a second *Zeugrhabdotus* survivor species or is a form that evolved from *Z. sigmoides*. **Occurrence:** Zone NP5; TDP Sites 27 and 37.

Zeugrhabdotus sigmoides (Bramlette & Sullivan, 1961) Bown & Young, 1997 Pl. 4, figs 27-29

Cenozoic muroliths

Order ZYGODISCALES **Young & Bown, 1997**

Family **PONTOSPHAERACEAE** Lemmermann, 1908

Genus *Pontosphaera* Lohmann, 1902

Remarks: The oldest representatives of this genus (e.g., *P. plana*) are typically recorded from the uppermost Paleocene or lower Eocene (Zones NP9-10). The middle Paleocene (Zone NP5) representatives, documented here, are relatively small and fragile compared to younger pontosphaerids and are probably only present in Paleocene sediments when preservation is good. The group, in general, is relatively preservation sensitive, for example, they are poorly represented in deep-sea sediments deposited close to the CCD (Palike et al., 2010).

Pontosphaera plana (Bramlette & Sullivan, 1961) Haq, 1971

Pl. 4, figs 30-34; Pl. 12, figs 6-7 **Remarks**: *Pontosphaera plana* is one of the oldest recorded species of the genus *Pontosphaera*, but is not typically documented in the fossil record in sediments older than latest Paleocene. The specimens seen here are from the oldest recovered Paleocene samples, assigned to Zone NP5. These specimens are smaller (4.0-6.5 µm) than the type material (7-11 µm) however an increase in coccolith size early in species ranges is relatively typical of coccolithophores and so the name *P. plana* has been applied here. Sullivan (1964) proposed the name *inconspicuus* for smaller specimens (6.0-9.0µm), considered a junior synonym here. **Range:** Zones NP5-NP21?.

Pontosphaera veta sp. nov.

Pl. 4, figs 35-40; Pl. 12, fig. 8. **Derivation of name**: From *vetus*, meaning 'ancient', referring to the age of this species of *Pontosphaera*. **Diagnosis**: Small to medium-sized *Pontosphaera* with narrow rim and wide central area spanned by a finely perforate plate. The small perforations are circular to elongate and irregularly distributed, but are typically arranged in three cycles. **Differentiation**: Distinguished from other *Pontosphaera* species by the finely perforate central area plate. It is also significantly older than previously described species in this genus. **Dimensions**: L = 6µm (range 5.6-7.2µm. **Holotype**: Pl. 4, fig. 37. **Paratypes**: Pl. 4, fig. 38; Pl.4, fig. 40, Pl. 12, fig. 8. **Type locality**: TDP Site 37, Kimamba Hill, Kilwa, Tanzania. **Type level**: Middle Paleocene (Selandian), Sample TDP37/10-1, 42 cm (Zone NP5). **Occurrence**: Zone NP5; TDP Sites 27 and 37.

Family **ZYGODISCAEAE** Hay & Mohler, 1967

Genus *Lophodolithus* Deflandre in Deflandre & Fert, 1954

Lophodolithus nascens Bramlette & Sullivan, 1961 Pl. 5, figs 18-19

Genus *Zygodiscus* Bramlette & Sullivan, 1961

Zygodiscus cearae (Perch-Nielsen, 1977) Bown & Dunkley Jones, 2006 Pl. 5, figs 16-*17*

Zygodiscus sheldoniae Bown, 2005 Pl. 5, fig. 20

Zygodiscus cf. Z*. sheldoniae* Bown, 2005 Pl. 5, fig. 21

Genus *Neochiastozygus* Perch-Nielsen, 1971

Neochiastozygus concinnus (Martini, 1961) Perch-Nielsen, 1971 Pl. 4, figs 41-42

Neochiastozygus distentus (Bramlette & Sullivan, 1961) Perch-Nielsen, 1971 Pl. 5, fig. 8

Neochiastozygus imbriei Haq & Lohmann, 1975 Pl. 4, figs 43-48

Neochiastozygus junctus (Bramlette & Sullivan, 1961) Perch-Nielsen, 1971 Pl. 4, fig. 51

Neochiastozygus modestus Perch-Nielsen, 1971 Pl. 4, figs 52-55; Pl. 12, fig. 9

Neochiastozygus perfectus Perch-Nielsen, 1971 Pl. 4, figs 49-50

Neochiastozygus rosenkrantzii (Perch-Nielsen, 1971) Varol, 1989 Pl. 5, figs 6-7

Neochiastozygus substrictus Bown, 2005 Pl. 5, figs 1-5

Genus *Neococcolithes* Sujkowski, 1931

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

Pl. 5, figs 9-15; Pl. 12, fig. 10 **Remarks**: Typically documented in the fossil record from the upper Paleocene, but small forms are recorded here (rarely) from the oldest recovered Paleocene samples, which are assigned to Zone NP5 (see also Perch-Nielsen, 1985). **Occurrence:** Zones NP5-7, TDP19, 27 and 37.

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

Family **CALCIOSOLENIACEAE** Kamptner, 1927

Genus *Calciosolenia* Gran, 1912

Calciosolenia aperta (Hay & Mohler, 1967) Bown, 2005 Pl. 5, figs 25-26; Pl. 13, fig. 1

Calciosolenia fossilis (Deflandre *in* Deflandre & Fert, 1954) Bown *in* Kennedy *et al*., 2000 Pl. 5, figs 22-24; Pl. 13, fig. 2

Calciosolenia sp. A

Pl. 13, fig. 3. **Remarks**: Narrow *Calciosolenia* coccolith with apparently imperforate plate spanning the central area. **Occurrence:** Zone NP6, TDP Site 19.

Family **RHABDOSPHAERACEAE** Haeckel, 1894

Genus *Blackites* Hay & Towe, 1962

Pl. 5, fig. 27; Pl. 13, figs 4-7 **Remarks**: The oldest representatives of this genus have previously been recorded from the uppermost Paleocene or lower Eocene (Zones NP9-10) (e.g., Bramlette & Sullivan, 1961; Bown, 2010). The very small specimens seen here from Zone NP6, in both SEM and LM, are the oldest *Blackites* yet recorded. *Blackites* coccoliths are typically lost from moderate to poorly preserved assemblages, but these early forms are especially small and fragile and are probably only present in Paleocene sediments when preservation is exceptionally good.

Blackites cf. *B. morionum* (Deflandre *in* Deflandre & Fert, 1954) Varol, 1989

Pl. 5, figs 27. **Remarks**: Very small *Blackites* with broad, low, domed spine. **Occurrence:** Zone NP7, TDP 19.

Blackites sp. B of Bown, 2010

Pl. 13, figs 4, 5, 7. **Remarks**: A small *Acanthoica*-like coccolith (i.e., lacking the large, multicyclic spines of typical *Blackites*) that has a rim, radial cycle and lamellar cycle that forms a low cone (see terminology in Young et al., 2003 and Dunkley Jones et al., 2009). Retained within *Blackites* here because the specimen reported from TDP Site 14 (Bown, 2010) was found within a cluster of *Blackites* coccoliths that may represent a collapsed coccosphere, therefore indicating that polymorphism may include these less spinose, i.e., *Acanthoica*-like, forms. **Occurrence:** Zones NP6-7, TDP Site 19; Subzone NP9b, TDP Site 14 (Bown, 2010).

Blackites sp. D

Pl. 13, fig. 6. **Remarks**: A minute *Acanthoica*-like coccolith (i.e., lacking the large, multicyclic spines of typical *Blackites*) that has a narrow rim, radial cycle and lamellar cycle that is not raised (see terminology in Young et al., 2003 and Dunkley Jones et al., 2009). With reference to living representatives of this group, this specimen may represent one of a variety of morphologies that was present on varimorphic coccopheres. **Occurrence:** Zone NP6, TDP 19.

INCERTAE SEDIS aff. family RHABDOSPHAERACEAE Haeckel, 1894

Genus *Solisphaera* Bollmann et al., 2006

Pl. 13, figs 14-18. **Remarks:** This extant genus has polymorphic coccospheres bearing small, simple coccoliths together with coccoliths having longitudinal blade-like processes (Young et al., 2003;

Bollmann et al., 2006). The processes are formed from miniscule (< 0.5 μm) rhombic elements arranged in an imbricate pattern. Similar processes are present in the Tanzanian Paleogene nannofossil assemblages (e.g., Bown et al., 2009), but they are slightly larger than extant specimens, the constituent elements are more elongate, and the attached basal coccoliths have not been observed. However, simple coccoliths have been found next to the 'processes', within clusters possibly representing collapsed coccospheres, e.g., Pl. 13, fig. 16. Two new *Solisphaera* species are described here but for the reasons given above, the generic assignment is tentative.

Solisphaera tegula sp. nov.

Pl. 13, figs 14-15. **Derivation of name**: From *tegula*, meaning 'tile', referring to the trapezoid shape of this species. **Diagnosis**: Small, broad, flat or slightly curving, tapered-trapezoid processes formed from miniscule, overlapping, elongate elements. The elements are arranged in over 30 rows and slope from upper left to lower right. **Remarks:** The younger, Middle Eocene specimens have an additional row of elements with different orientation at the narrower end of the process, which may be where the process joined the basal coccolith (Pl. 13, fig. 15). **Differentiation**: In extant species the elements forming the process, slope from lower left to upper right. This gives the impression of a major difference in orientation, but may simply be a product of different element shape (i.e., elongation) with no change in crystallographic orientation. The 'basal' cycle is not so conspicuous in published images of extant specimens. The fossil specimens are comparable to the living species *Solisphaera emidasia* Bollmann et al., 2006 and *S. blagnacensis* Bollmann et al., 2006. **Dimensions**: L = 2.4-3.3μm; W = 2.1-2.9μm. **Holotype**: Pl. 13, fig. 14. **Paratype**: Pl. 13, fig. 15. **Type locality**: TDP Site 19, Pande, Tanzania. **Type level**: Upper Paleocene, Sample TDP19/26-1, 25 cm (Zone NP6). **Occurrence**: Zone NP6; TDP Site 19. **Range:** Middle Paleocene to Middle Eocene (Zones NP6-14a/15b); TDP Sites 19, 13 (Pande) and 20 (Kilwa).

Solisphaera palmula sp. nov.

Pl. 13, figs 16-18. **Derivation of name**: From *palmula*, meaning 'blade of an oar', referring to the curving, blade-like morphology of this species. **Diagnosis**: Very small, narrow, flat or slightly curving, tapered-trapezoid processes formed from miniscule, overlapping, elongate elements. The elements are arranged in 15-20 rows that slope from upper left to lower right. **Remarks:** Two simple coccoliths, with very narrow rim, central plate and no process, are associated with a group of specimens that may be a collapsed coccosphere (Pl. 13, fig. 16); these may represent polymorphic coccoliths similar to those seen in extant species of *Solisphaera*. **Differentiation**: See the discussion of comparisons with extant species for *S. tegula*, above. *Solisphaera palmula* is smaller, narrower and more elongate than *S. tegula*. **Dimensions**: L = 1.6-2.2µm; W = 0.8-1.1µm. **Holotype**: Pl. 13, fig. 16. **Paratype**: Pl. 13, fig. 18. **Type locality**: TDP Site 19, Pande, Tanzania. **Type level**: Upper Paleocene, Sample TDP19/26-1, 25 cm (Zone NP6). **Occurrence**: Zone NP6; TDP Site 19. **Range**: Middle-Upper Paleocene Zones NP5-6; TDP Sites 19 and 27.

Family **SYRACOSPHAERACEAE** Lemmermann, 1908

Genus *Syracosphaera* Lohmann, 1902

Remarks: The oldest representatives of this genus are typically recorded from the upper Eocene (e.g., Dunkley Jones et al., 2009) but they are rare and their presence is dependent on good quality preservation. The specimens recorded here from Zone NP7 are the oldest yet that can be attributed to this important extant genus.

Syracosphaera cf. *S. tanzanensis* Bown, 2005

Pl. 13, fig. 11. **Remarks:** Muroliths with typical *Syracosphaera* morphology, comprising a high rim, narrow radial lath cycle and a broad, raised central plate formed of fused elements (see terminology in Young et al., 2003 and Dunkley Jones et al., 2009). The scanning electron micrographs of *S. tanzanensis* shown by Dunkley Jones et al. (2009) have a narrower and spine-bearing central process, hence the tentative affiliation given here. **Occurrence:** Zone NP7, TDP 19.

HOLOCOCCOLITHS

Family **CALYPTROSPHAERACEAE** Boudreaux & Hay, 1967

Genus *Clathrolithus* Deflandre *in* Deflandre & Fert, 1954

Clathrolithus ellipticus Deflandre in Deflandre & Fert, 1954 Pl. 5, fig 28

Genus *Holodiscolithus* Roth, 1970

Holodiscolithus serus Bown, 2005 Pl. 6, figs 1-4

Holodiscolithus solidus (Deflandre *in* Deflandre & Fert, 1954) Roth, 1970 Pl. 5, figs 32-37

Holodiscolithus cf. *H. solidus* (Deflandre *in* Deflandre & Fert, 1954) Roth, 1970

Pl. 5, fig. 29-31 **Remarks:** Similar to *H. solidus* but the central area is narrow and only four diagonal 'bars' are clearly visible. Comparable to *Multipartis ponticus* Varol, 1989 but the rim is not subdivided into separate blocks.

Genus *Lanternithus* Stradner, 1962

Lanternithus duocavus Locker, 1967 Pl. 5, fig. 38-46

Lanternithus simplex Bown, 2005 Pl. 5, fig. 47-50

Lanternithus cf. *L. simplex* Bown, 2005

Pl. 5, fig. 51-55 **Remarks:** Small (3.1-3.2µm), elliptical holococcoliths composed of four blocks with an indistinct central hole or depression. Typically, the extinction lines are axial when the coccolith is orientated at 0° and diagonal at 45°. **Differentiation:** Smaller than *Lanternithus simplex* and with a smaller central pore or depression. **Occurrence**: Zone NP5-7; TDP Sites 19 and 27.

Lanternithus unicavus sp. nov.

Pl. 5, fig. 56-60 **Derivation of name**: From *uni*, meaning 'one', and '*cavus*' meaning 'hole or hollow' referring to the central hole in this species. **Diagnosis:** Small, elliptical holococcoliths with two small blocks at either end of the lith and a circular central hole or depression, which is dark in XPL. In XPL, the blocks are relatively dark when the coccolith is orientated at 0° and brightest at 45°. **Differentiation:** Differentiated from other *Lanternithus* by the single central hole and small, distinct blocks at each end of the coccolith. Previously illustrated as *Lanternithus* sp. II by Varol (1989). **Holotype dimensions**: L = 3.5µm. **Holotype**: Pl. 5, fig. 57. **Paratype**: Pl.5, fig. 59. **Type locality**: TDP Site 37, Kimamba Hill, Kilwa, Tanzania. **Type level**: Middle Paleocene (Selandian), Sample TDP37/11-1, 0 cm (Zone NP5). **Occurrence**: Zone NP5; TDP Sites 27 and 37.

Genus *Munarinus* Risatti, 1973

Munarinus emrei Varol, 1989 Pl. 6, fig. 38-39

Genus *Semihololithus* Perch-Nielsen, 1971

Semihololithus cf. *S. biscayae* Perch-Nielsen, 1971 Pl. 6, fig. 12

Semihololithus dimidius Bown, 2005 Pl. 6, fig. 6-11

Semihololithus tentorium Bown, 2005 Pl. 6, fig. 13-19

Genus *Youngilithus* Bown, 2005

Youngilithus quadraeformis Bown, 2005

Pl. 6, fig. 20-26. **Remarks**: Includes specimens that are slightly larger than the type specimens from the middle Eocene of Tanzania (Bown, 2005), but which are otherwise very similar. **Occurrence**: Middle Paleocene to Middle Eocene (Zones NP5- Subzone NP15c); TDP sites 27 and 2.

Youngilithus transversipons sp. nov.

Pl. 6, fig. 29-31. **Derivation of name**: From *tranversus*, meaning 'oblique', and '*pons*' meaning bridge, referring to the central area bars of this species. **Diagnosis**: Elongate rhomboid liths with three oblique, parallel, central area bars. Low birefringence image in XPL. **Holotype dimensions**: L = 6.3µm. **Holotype**: Pl.6, fig.29. **Type locality**: TDP Site 19, Pande, Tanzania. **Type level**: Upper Paleocene (Selandian), Sample TDP19/28-2, 6 cm (Zone NP5). **Occurrence**: Middle-Upper Paleocene Zone NP6; TDP Site 19.

Youngilithus bipons sp. nov.

Pl. 6, fig. 27-28. **Derivation of name**: From *bi*, meaning 'two', and '*pons*' meaning bridge, referring to the central area bars of this species. **Diagnosis**: Rhomboid liths with small, marginal projections from the rim and two oblique, parallel, central area bars. Low birefringence image in XPL. **Holotype dimensions**: L = 6.2µm. **Holotype**: Pl.6, fig.27. **Type locality**: TDP Site 27, Kimamba Hill, Kilwa, Tanzania. **Type level**: Middle Paleocene (Selandian), Sample TDP27/7-1, 6 cm (Zone NP5). **Occurrence**: Middle Paleocene Zone NP5; TDP Site 27.

Genus *Zygrhablithus* Deflandre, 1959

Zygrhablithus bijugatus bijugatus (Deflandre *in* Deflandre & Fert, 1954) Deflandre, 1959 Pl. 6, figs 32-35; Pl. 13, figs 8-9

Holococcolith sp. 1

Pl. 6, figs 36-37. **Remarks**: Hollow, spherical lith (diameter ~3.8µm) with narrow neck at one end. Similar to the Cretaceous *Laguncula dorotheae* Black, 1971 in general form. **Occurrence**: Middle Paleocene (Zone NP5); TDP Site 37.

HAPTOPHYTE NANNOLITHS

Family **BRAARUDOSPHAERACEAE** Deflandre, 1947

Genus *Braarudosphaera* Deflandre, 1947

Braarudosphaera bigelowii (Gran & Braarud, 1935) Deflandre, 1947 Pl. 6, fig. 41

Braarudosphaera insecta sp. nov.

Pl. 6, fig. 43-44. **Derivation of name**: From *insecta*, meaning 'notch', referring to the outline of these pentaliths. **Diagnosis**: Large *Braarudosphaera* with pentaliths that have crenulate edges. The protruding crenulations primarily occur where the sutures meet the pentalith edge. **Differentiation:** The crenulate outline is unlike most other *Braarudosphaera* species and it is much less indented than *Micrantholithus bramlettei* Deflandre in Deflandre & Fert, 1954. **Holotype dimensions**: L = 11.6µm. **Holotype**: Pl. 6, fig. 43. **Paratype**: Pl. 6, fig. 44. **Type locality**: TDP Site 19, Pande, Tanzania. **Type level**: Upper Paleocene, Sample TDP19/13-1, 36 cm (Zone NP7). **Occurrence**: Zone NP5-7; TDP Sites 19 and 27.

Braarudosphaera perampla Bown, 2010 Pl. 6, fig. 42, 45

Braarudosphaera rosa Levin & Joerger 1967 Pl. 6, fig. 40

Remarks: These symmetrical *Braarudosphaera* specimens with rounded tips are similar to *B. rosa* described from the Oligocene but they have slightly indented sides. Black (1973) also described symmetrical mid-Cretaceous *Braarudosphaera* forms with indented (*Braarudosphaera primula*) and straight sides (*Braarudosphaera regularis*). **Occurrence:** Zone NP7, TDP Site 19.

Braarudosphaera sequela Self-Trail, 2011 Pl. 6, fig. 46

Remarks: Similar in form to the mid-Cretaceous (Albian-Cenomanian) species *B. africana*, but larger and considerably younger in age. **Occurrence:** Zone NP7, TDP Site 19; NP10 (Self-Trail, 2011).

Genus *Micrantholithus* Deflandre in Deflandre & Fert, 1954

Micrantholithus astrum Bown, 2005 Pl. 6, fig. 47; Pl. 13, fig. 12

Micrantholithus breviradiatus Bown, 2005 Pl. 6, fig. 48

Micrantholithus disculus (Bramlette & Riedel, 1954) Bown, 2005

Pl. 6, figs 49-51; Pl. 13, fig. 13. **Remarks:** Previously spelt *discula* (Bown, 2005) and corrected here to *disculus*.

Micrantholithus flos Deflandre *in* Deflandre & Fert, 1954 Pl. 7, fig. 1

Micrantholithus pinguis Bramlette & Sullivan, 1961 Pl. 7, figs 2-6

EXTINCT NANNOLITHS

Order DISCOASTERALES **Hay, 1977 emend. Bown, 2010**

Family **DISCOASTERACEAE** Tan, 1927

Genus *Discoaster* Tan, 1927

Discoaster binodosus Martini, 1958 Pl. 7, figs 17-18

Discoaster mediosus Bramlette & Sullivan, 1961 Pl. 7, figs 15-16

Discoaster mohleri Bramlette & Percival, 1971 Pl. 7, figs 7-10

Discoaster splendidus Martini, 1960 Pl. 7, figs 11-14

Family **FASCICULITHACEAE** Hay & Mohler, 1967

Pl. 8, figs 1-37. **Remarks:** Aubry et al. (2011) have recently introduced a number of new genera, which subdivide the fasciculith group, in particular reflecting the diversity of form, which accompanies their early evolution and diversification in the late Danian/early Selandian (Zones NP4-5 equivalent). These include the earliest fasciculiths (termed *Gomphiolithus* in Aubry et al., 2011), stellate forms with two superimposed cycles (*Diantholitha*), and forms with three discrete superimposed cycles (*Lithoptychius*). These authors also reassigned a number of well-established *Fasciculithus* species into *Lithoptychius*, including *F. pileatus*, *F. ullii*, *F. janii* and *F. chowii*. Here, I have retained the *Fasciculithus* nomenclature for these latter taxa, awaiting further support from stratigraphic and phylogenetic information, which will clarify the relationships between these taxa.

Genus *Diantholitha* Aubry *in* Aubry et al., 2011

Diantholitha mariposa Rodriguez & Aubry *in* Aubry et al., 2011 Pl. 9, figs 1-13

Diantholitha sp.

Pl. 9, figs 14-40 **Remarks:** In top view, the *Diantholitha* specimens show two circular birefringent cycles, but the largest may have a rather ragged outline. They resemble *Fasciculithus* but have two clearly distinct cycles, and *Bomolithus* but the cycles are birefringent.

Genus *Fasciculithus* Bramlette & Sullivan, 1961

Fasciculithus involutus Bramlette & Sullivan, 1961 Pl. 8, figs 6-12

Fasciculithus janii Perch-Nielsen, 1971

Pl. 8, fig. 35-37. **Remarks**: This *Fasciculithus* species, with a flaring column and distinct distal cycle that is significantly broader than the column, is a very distinct morphotype, to which a number of names have previously been applied. *Fasciculithus pileatus* and *F. merloti* have a distal cycle that is the same diameter as the column, and in *F. stonehengei* the distal cycle is slightly wider. The SEM holotype of *F. janii* appears to represent this form but the paratype LMs show a different fasciculith. **Occurrence**: Zone NP5; TDP Site 37. Upper Zone NP4-NP6 (Varol, 1989).

Fasciculithus lilianiae Perch-Nielsen, 1971 Pl. 8, figs 24-25

Fasciculithus pileatus Bukry, 1973 Pl. 8, figs 30-32

Fasciculithus cf. *F. pileatus* Bukry, 1973 Pl. 8, figs 33-34

Fasciculithus thomasi Perch-Nielsen, 1971 Pl. 8, figs 20-23

Fasciculithus tonii Perch-Nielsen, 1971 Pl. 8, figs 26-29

Fasciculithus tympaniformis Hay & Mohler *in* Hay *et al*., 1967 Pl. 8, figs 1-5

Fasciculithus vertebratoides Steurbaut & Sztrákos, 2008 Pl. 8, figs 13-16

Genus *Lithoptychius* Aubry *in* Aubry et al., 2011

Lithoptychius schmitzii Monechi et al., 2013 Pl. 8, figs 38-39

Family **HELIOLITHACEAE** Hay & Mohler, 1967

Genus *Bomolithus* Roth, 1973

Pl. 7, figs 19-45. **Description:** Discoidal discoasteralids with a wide non-birefringent cycle and at least one narrower birefringent cycle, i.e., narrower than the diameter of the nannolith. The non-birefringent cycle is comparable to rosette discoasters is morphology.

Bomolithus bramlettei (Bukry & Percival, 1971) Young & Bown, 2014

Pl. 7, figs 19-25 **Description**: Medium to large sized (herein ~7.5-8.5μm), rosette-shaped discoasteralid with 17-21 rays and a narrow birefringent cycle (typically less than half to a quarter of the total diameter). The birefringent cycle often has a ragged outline. **Remarks**: Martini (1958) first used the species *bramlettei* for a 'discoaster' but this taxon was subsequently reassigned to *Trochastrites* (Stradner, 1961) and so the later described species *Discoasteroides bramlettei* Bukry

& Percival, 1971 is available for use, see also Young and Bown (2014). **Synonym:** *Markalius variabilis* Perch-Nielsen 1977. **Occurrence**: Zone NP6, TDP Site 19. **Range** Zone NP6-7.

Bomolithus conicus (Perch-Nielsen, 1971) Perch-Nielsen, 1984 Pl. 7, figs 26-27

Remarks: Medium sized (herein ~5.5µm) *Bomolithus* with relatively low, broad birefringent cycle (close to or greater than half the lith diameter). **Occurrence**: NP7, TDP Site 19.

Bomolithus elegans Roth, 1973 Pl. 7, figs 28-45

Remarks: Medium to large (herein ~7.5-12.0µm) rosette-shaped discoasteralid with prominent, broad birefringent cycle (greater than half the lith diameter). Often seen in side view (Pl. 7, figs 40-45). Typically larger than *B. conicus* and with a broader, higher birefringent cycle. **Occurrence**: NP6-7, TDP Site 19.

Genus *Heliolithus* Bramlette and Sullivan, 1961

Heliolithus kleinpellii Sullivan, 1964 Pl. 7, figs 46-51

Family **SPHENOLITHACEAE** Deflandre, 1952

Genus *Sphenolithus* Deflandre in Grassé, 1952

Sphenolithus anarrhopus Bukry & Bramlette 1969 Pl. 9, figs 44-47

Sphenolithus moriformis (Brönnimann & Stradner, 1960) Bramlette & Wilcoxon, 1967 Pl. 9, figs 41-43

Family **LAPIDEACASSACEAE** Bown & Young 1997

Genus *Lapideacassis* Black 1971

Lapideacassis sp. Pl. 9, figs 48-51

INCERTAE SEDIS SMALL COCCOLITHS

Genus *Gladiolithus* Jordan & Chamberlain, 1993

Gladiolithus flabellatus (Halldal & Markali, 1955) Jordan & Chamberlain, 1993

Pl. 13, figs 19, 21. **Remarks**: *Gladiolithus* is abundant in Eocene sediments from Tanzania (Bown et al., 2009) and the occurrences here establish its presence in the Paleocene. The records from Zone NP5 at TDP Site 27 are the oldest yet determined for this taxon. Alongside the observation of *Solisphaera* like coccoliths in Zone NP6, this suggests that a relatively diverse, specialized lower photic zone coccolithophore assemblage was established relatively soon (no more than ~5Ma) after the K/Pg boundary extinctions (see also Bown et al, 2009).

Occurrence: Zones NP5-NP23, all Paleogene TDP sites.

Gladiolithus? sp. A

Pl. 13, fig. 20. **Remarks**: Very small (<2µm) murolith coccolith with narrow protolith rim and central area spanned by a plate. Sometimes associated with *Gladiolithus* coccoliths and may represent a very short variant within this group. **Occurrence:** Zone NP6; TDP Site 19.

Indeterminate coccoliths

Murolith sp. A

Pl. 12, fig. 13. **Remarks**: Very small (<2µm) murolith (loxolith) coccoliths with clockwise imbrication direction in the outer rim cycle, suggesting affiliation within a Mesozoic survivor lineage. The central area is spanned by a narrow longitudinal bar and around 20 lateral bars. **Occurrence:** Zone NP6; TDP Site 19.

Murolith sp. B

Pl. 12, fig. 14. **Remarks**: Very small (<3µm) murolith coccoliths with broad, high loxolith rim having clockwise imbrication direction in the outer cycle, suggesting affiliation within a Mesozoic survivor lineage. The central area is spanned by narrow axial cross bars. **Differentiation:** Resembles the small Paleogene murolith species, *Staurolithites primaevus*, described only from LM images by Bown (2005). **Occurrence:** Zone NP6; TDP Site 19.

Coccolith indet.

Pl. 12, fig. 12. **Remarks**: Minute (<2µm) coccolith with flaring bicyclic rim and central area spanned by a plate. **Occurrence:** Zone NP6; TDP Site 19.

Placolith indet.

Pl. 12, fig. 11. **Remarks**: Very small (1.8µm), narrowly elliptical placolith with narrow central area spanned by a plate. **Occurrence:** Zone NP6; TDP Site 19.

INCERTAE SEDIS NANNOLITHS

Genus *Biantholithus* Bramlette & Martini, 1964

Biantholithus? *flosculus* Bown, 2005 Pl. 9, figs 52-54

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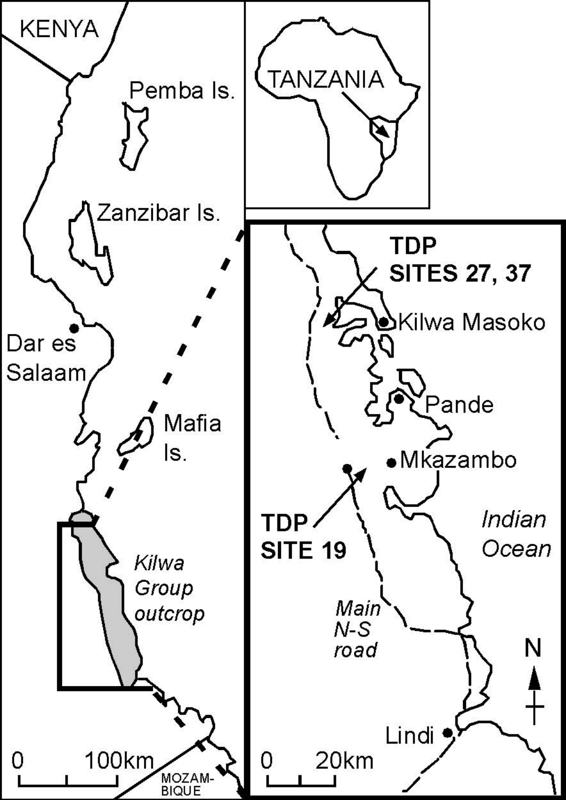
Captions

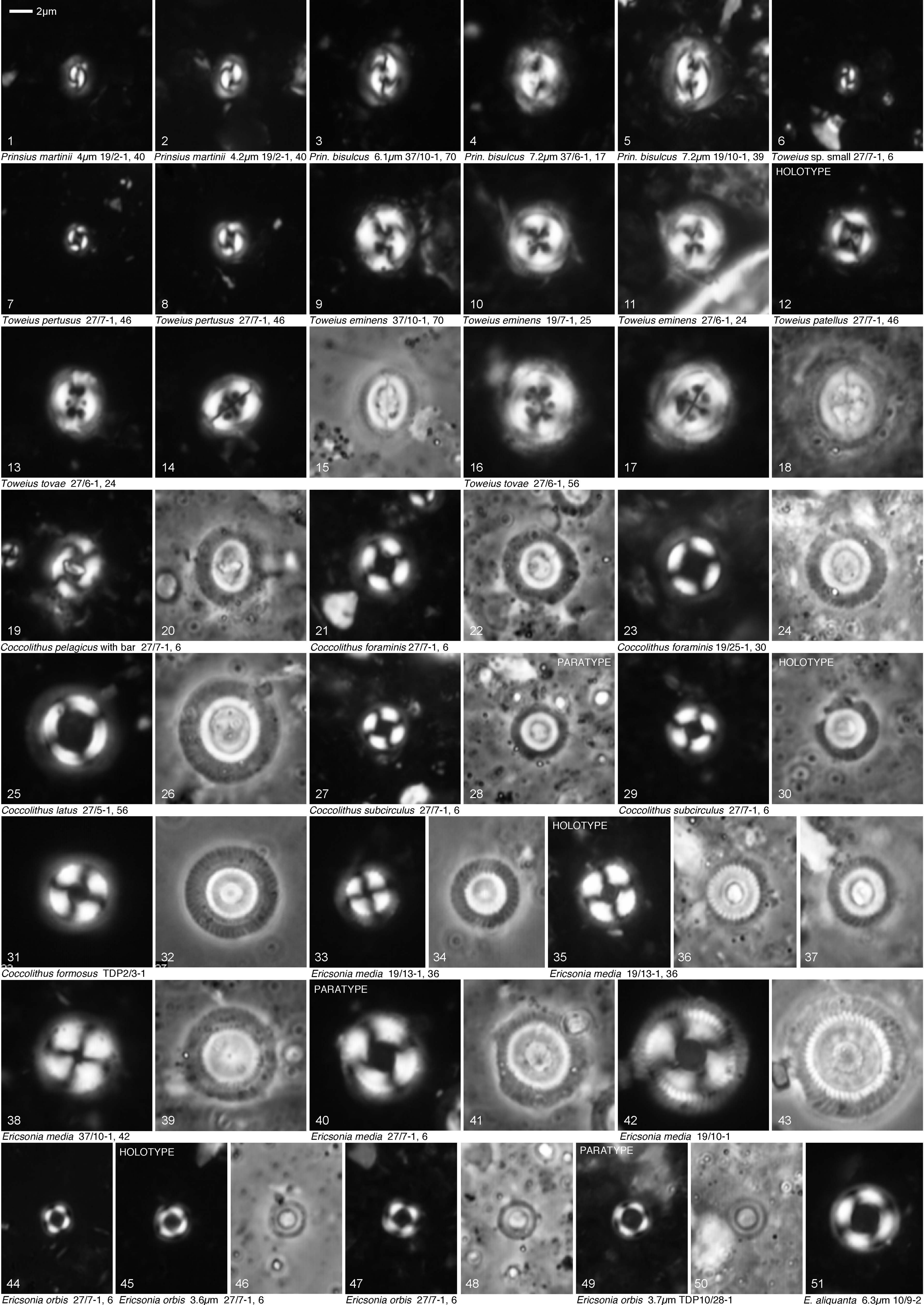
Figure 1. Location of the study area and TDP sites 19, 27 and 37.

Table 1. Stratigraphic range chart for nannofossil taxa from TDP Site 27. Species abundance: **A** >10/field of view (FOV), **C** 1-10/FOV, **F** 1/2-10 FOV, **R** 1/11-100 FOV, **•** <10 specimens observed (actual number observed given for very low abundances), **?** questionable occurrence. **S** is an identification based on scanning electron microscopy. Nannofossil abundance (with respect to all sedimentary particles in the smear slide): **A** >10%, **C** 1-10%, **F** 0.1-1%, **R** <0.1%, **VB** virtually barren (very low numbers of specimens), **B** barren. Nannofossil preservation: **G** good, **M** moderate, **P** poor.

Table 2. Stratigraphic range chart for nannofossil taxa from TDP Site 37. See Chart 1 caption for abbreviations, etc.

Table 3. Stratigraphic range chart for nannofossil taxa from TDP Site 19. See Chart 1 caption for abbreviations, etc.


KENYA
Pemba Is.
Zanzibar Is.
Dar es Salaam
Mafia Is.
Kilwa Group outcrop
0
100km
MOZAMBIQUE
TANZANIA
TDP SITES 27, 37
Kilwa Masoko
Pande
Mkazambo
TDP SITE 19
Indian Ocean
Main N-S road
N
Lindi
0
20km



1 *Prinsius martinii* 4μm 19/2-1, 40; 2 *Prinsius martinii* 4.2μm 19/2-1, 40; 3 *Prin. bisulcus* 6.1μm 37/10-1, 70; 4 *Prin. bisulcus* 7.2μm 37/6-1, 17; 5 *Prin. bisulcus* 7.2μm 19/10-1, 39; 6 *Toweius* sp. small 27/7-1, 6

7 *Toweius pertusus* 27/7-1, 46; 8 *Toweius pertusus* 27/7-1, 46; 9 *Toweius eminens* 37/10-1, 70; 10 *Toweius eminens* 19/7-1, 25; 11 *Toweius eminens* 27/6-1, 24; 12 *Toweius patellus* 27/7-1, 46

13–15 *Toweius tovae* 27/6-1, 24; 16–18 *Toweius tovae* 27/6-1, 56

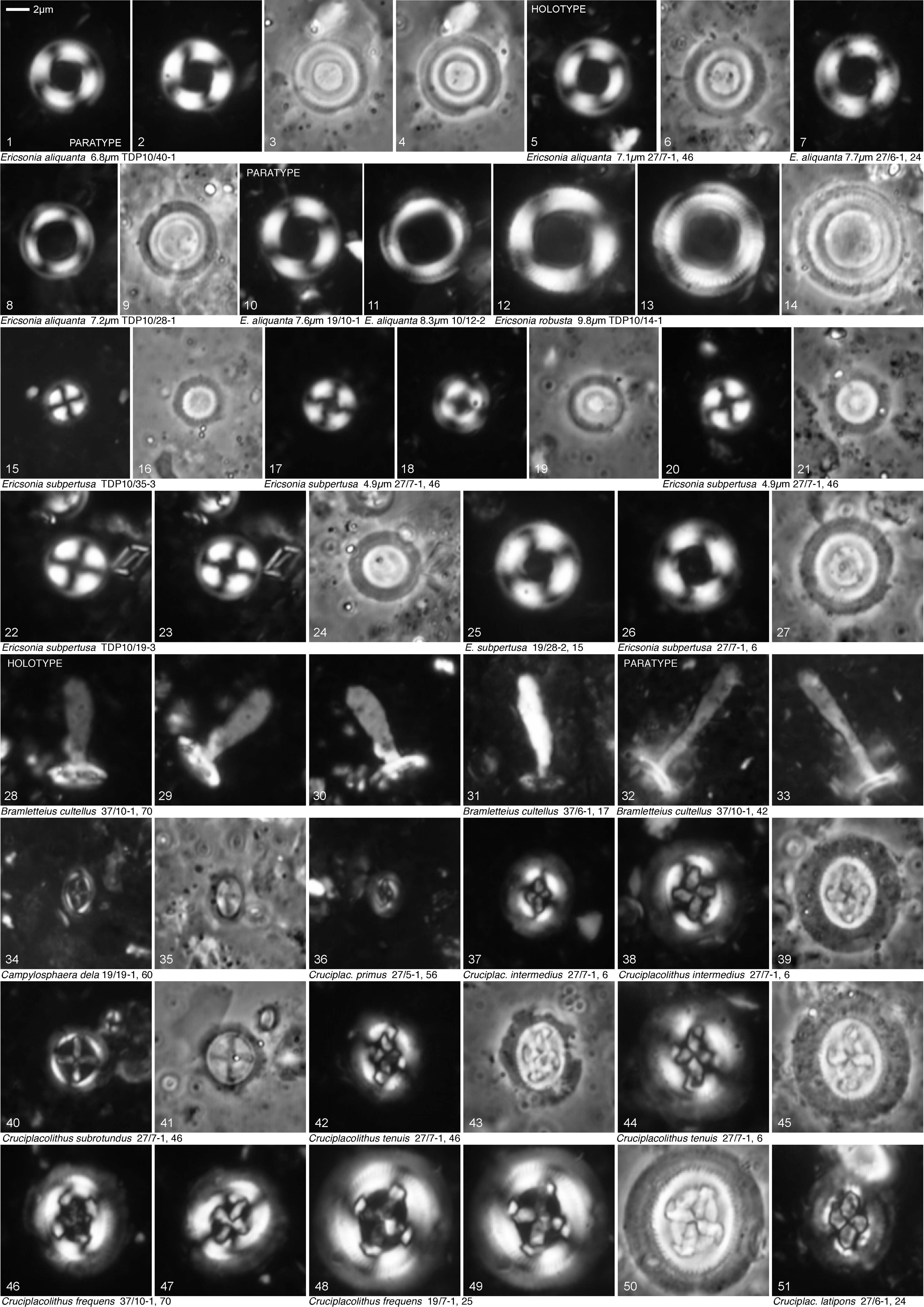
19–20 *Coccolithus pelagicus* with bar 27/7-1, 6; 21–22 *Coccolithus foraminis* 27/7-1, 6; 23–24 *Coccolithus foraminis* 19/25-1, 30

25–26 *Coccolithus latus* 27/5-1, 56; 27–28 *Coccolithus subcirculus* 27/7-1, 6; 29–30 *Coccolithus subcirculus* 27/7-1, 6

31–32 *Coccolithus formosus* TDP2/3-1; 33–34 *Ericsonia media* 19/13-1, 36; 35–37 *Ericsonia media* 19/13-1, 36

38–39 *Ericsonia media* 37/10-1, 42; 40–41 *Ericsonia media* 27/7-1, 6; 42–43 *Ericsonia media* 19/10-1

44 *Ericsonia orbis* 27/7-1, 6; 45–46 *Ericsonia orbis* 3.6μm 27/7-1, 6; 47–48 *Ericsonia orbis* 27/7-1, 6; 49–50 *Ericsonia orbis* 3.7μm TDP10/28-1; 51 *E. aliquanta* 6.3μm 10/9-2



Ericsonia aliquanta 6.8µm TDP10/40-1 (1–4); *Ericsonia aliquanta* 7.1µm 27/7-1, 46 (5–6); *E. aliquanta* 7.7µm 27/6-1, 24 (7)

Ericsonia aliquanta 7.2µm TDP10/28-1 (8–9); *E. aliquanta* 7.6µm 19/10-1 (10); *E. aliquanta* 8.3µm 10/12-2 (11); *Ericsonia robusta* 9.8µm TDP10/14-1 (12–14)

Ericsonia subpertusa TDP10/35-3 (15–16); *Ericsonia subpertusa* 4.9µm 27/7-1, 46 (17–19); *Ericsonia subpertusa* 4.9µm 27/7-1, 46 (20–21)

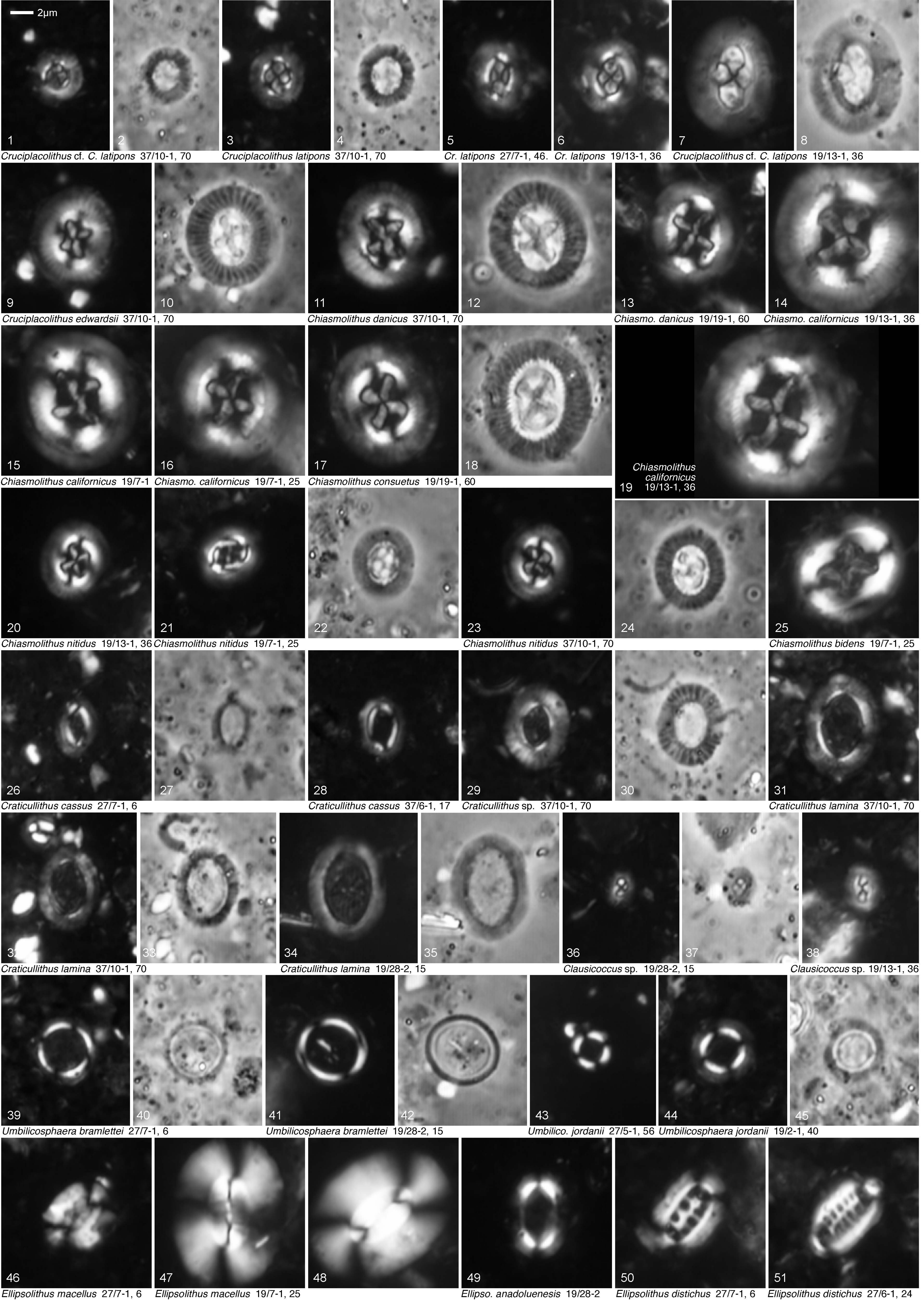
Ericsonia subpertusa TDP10/19-3 (22–24); *E. subpertusa* 19/28-2, 15 (25); *Ericsonia subpertusa* 27/7-1, 6 (26–27)

Bramletteius cultellus 37/10-1, 70 (28–30); *Bramletteius cultellus* 37/6-1, 17 (31); *Bramletteius cultellus* 37/10-1, 42 (32–33)

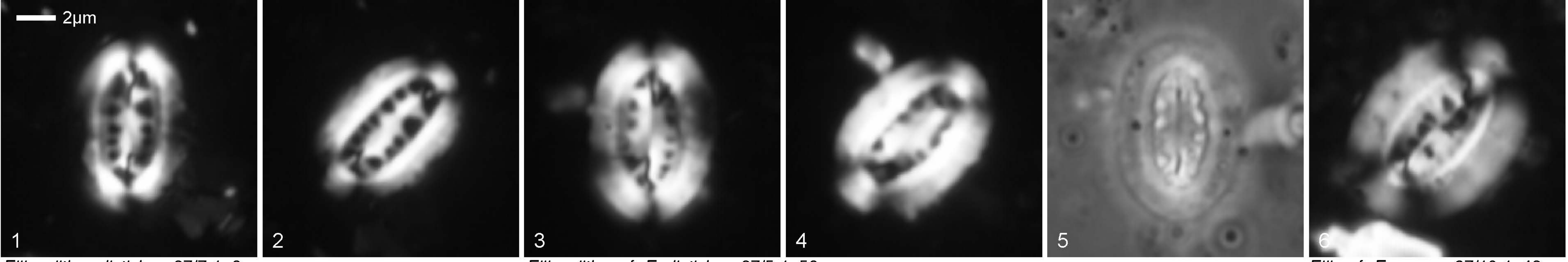
Campylosphaera dela 19/19-1, 60 (34–35); *Cruciplac. primus* 27/5-1, 56 (36); *Cruciplac. intermedius* 27/7-1, 6 (37); *Cruciplacolithus intermedius* 27/7-1, 6 (38–39)

Cruciplacolithus subrotundus 27/7-1, 46 (40–41); *Cruciplacolithus tenuis* 27/7-1, 46 (42–43); *Cruciplacolithus tenuis* 27/7-1, 6 (44–45)

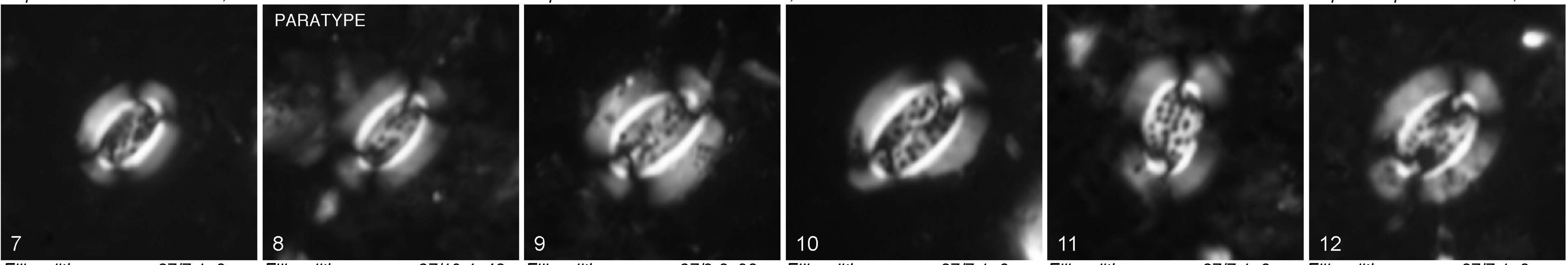
Cruciplacolithus frequens 37/10-1, 70 (46–47); *Cruciplacolithus frequens* 19/7-1, 25 (48–50); *Cruciplac. latipons* 27/6-1, 24 (51)



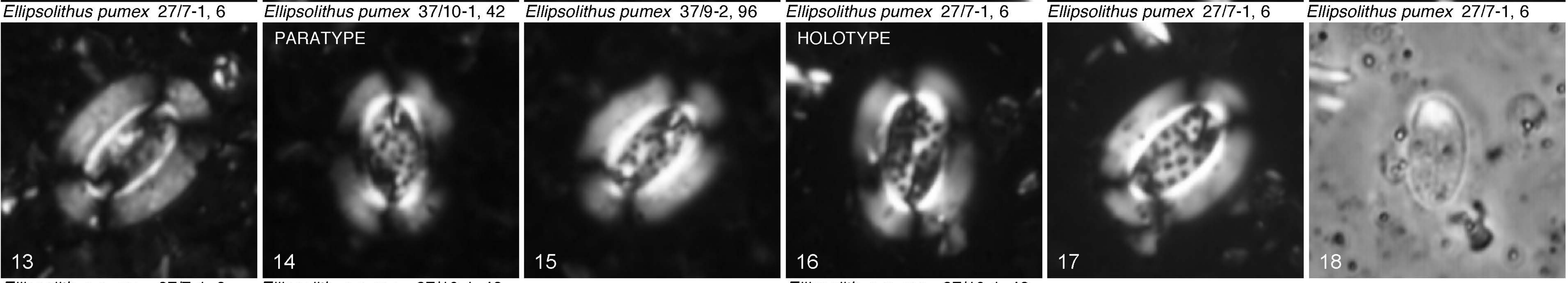
2μm
1 2 3 4 5 6 7 8
Cruciplacolithus cf. *C. latipons* 37/10-1, 70
Cruciplacolithus latipons 37/10-1, 70
Cr. latipons 27/7-1, 46.
Cr. latipons 19/13-1, 36
Cruciplacolithus cf. *C. latipons* 19/13-1, 36
9 10 11 12 13 14
Cruciplacolithus edwardsii 37/10-1, 70
Chiasmolithus danicus 37/10-1, 70
Chiasmo. danicus 19/19-1, 60
Chiasmo. californicus 19/13-1, 36
15 16 17 18
Chiasmolithus californicus 19/7-1
Chiasmo. californicus 19/7-1, 25
Chiasmolithus consuetus 19/19-1, 60
19
Chiasmolithus californicus 19/13-1, 36
20 21 22 23 24 25
Chiasmolithus nitidus 19/13-1, 36
Chiasmolithus nitidus 19/7-1, 25
Chiasmolithus nitidus 37/10-1, 70
Chiasmolithus bidens 19/7-1, 25
26 27 28 29 30 31
Craticullithus cassus 27/7-1, 6
Craticullithus cassus 37/6-1, 17
Craticullithus sp. 37/10-1, 70
Craticullithus lamina 37/10-1, 70
32 33 34 35 36 37 38
Craticullithus lamina 37/10-1, 70
Craticullithus lamina 19/28-2, 15
Clausicoccus sp. 19/28-2, 15
Clausicoccus sp. 19/13-1, 36
39 40 41 42 43 44 45
Umbilicosphaera bramlettei 27/7-1, 6
Umbilicosphaera bramlettei 19/28-2, 15
Umbilico. jordanii 27/5-1, 56
Umbilicosphaera jordanii 19/2-1, 40
46 47 48 49 50 51
Ellipsolithus macellus 27/7-1, 6
Ellipsolithus macellus 19/7-1, 25
Ellipso. anadoluenesis 19/28-2
Ellipsolithus distichus 27/7-1, 6
Ellipsolithus distichus 27/6-1, 24



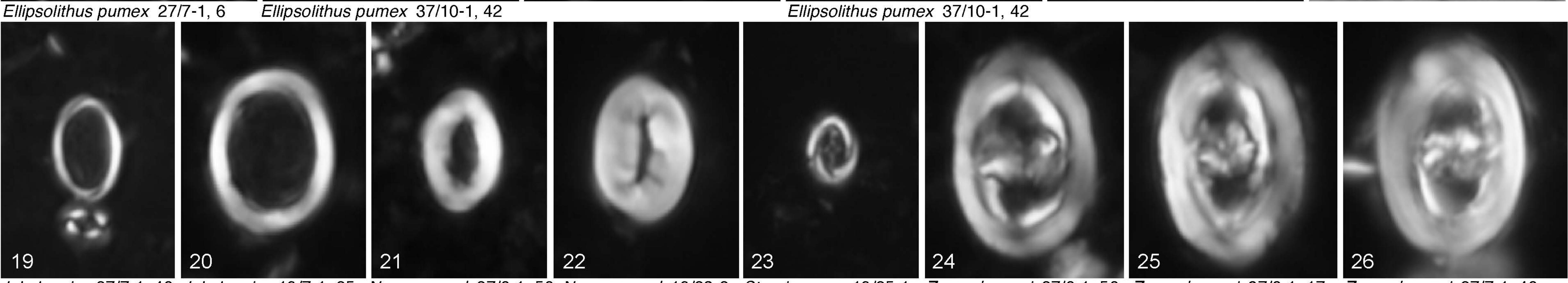
Ellipsolithus distichus 27/7-1, 6 *Ellipsolithus* cf. *E. distichus* 27/5-1, 56 *Ellip.* cf. *E. pumex* 37/10-1, 42



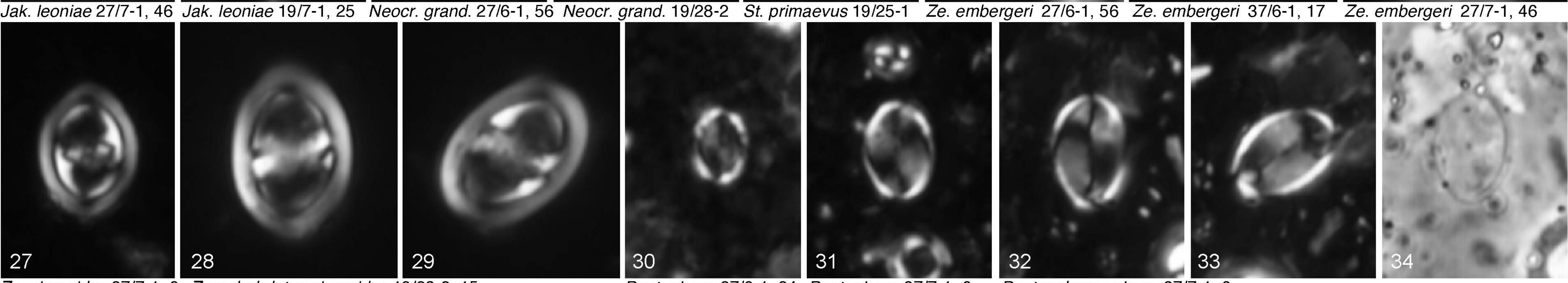
Ellipsolithus pumex 27/7-1, 6 *Ellipsolithus pumex* 37/10-1, 42 *Ellipsolithus pumex* 37/9-2, 96 *Ellipsolithus pumex* 27/7-1, 6 *Ellipsolithus pumex* 27/7-1, 6 *Ellipsolithus pumex* 27/7-1, 6



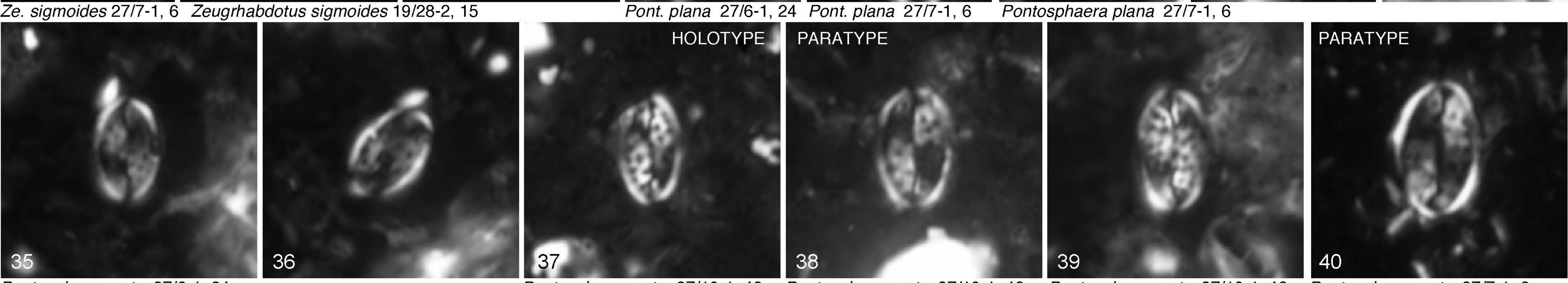
Ellipsolithus pumex 27/7-1, 6 *Ellipsolithus pumex* 37/10-1, 42 *Ellipsolithus pumex* 37/10-1, 42



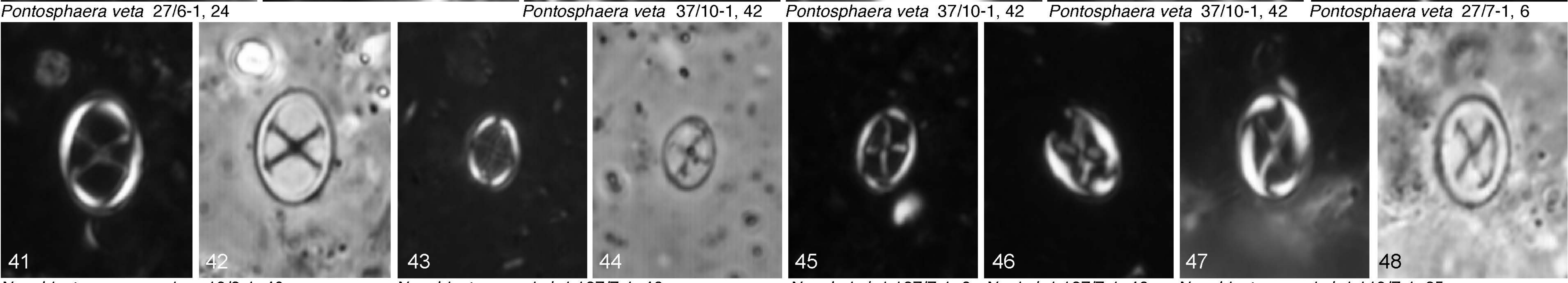
Jak. leoniae 27/7-1, 46 *Jak. leoniae* 19/7-1, 25 *Neocr. grand.* 27/6-1, 56 *Neocr. grand.* 19/28-2 *St. primaevus* 19/25-1 *Ze. embergeri* 27/6-1, 56 *Ze. embergeri* 37/6-1, 17 *Ze. embergeri* 27/7-1, 46



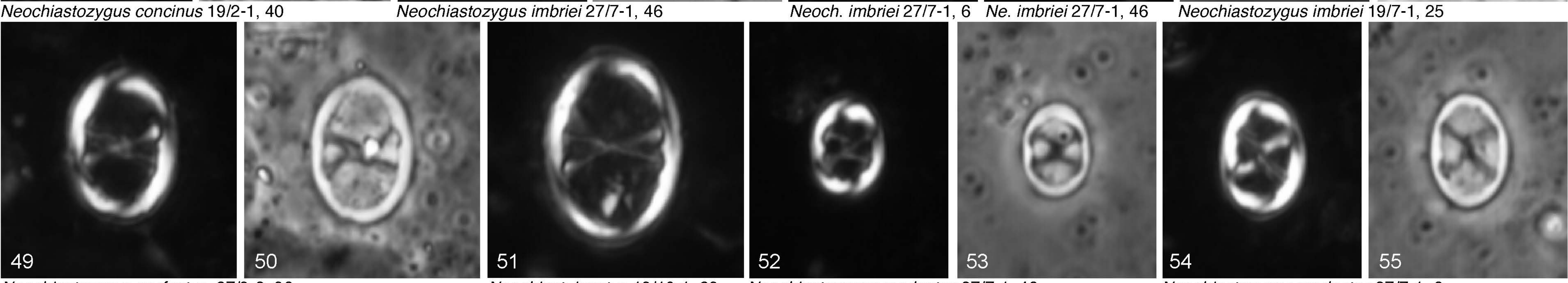
Ze. sigmoides 27/7-1, 6 *Zeugrhabdotus sigmoides* 19/28-2, 15 *Pont. plana* 27/6-1, 24 *Pont. plana* 27/7-1, 6 *Pontosphaera plana* 27/7-1, 6



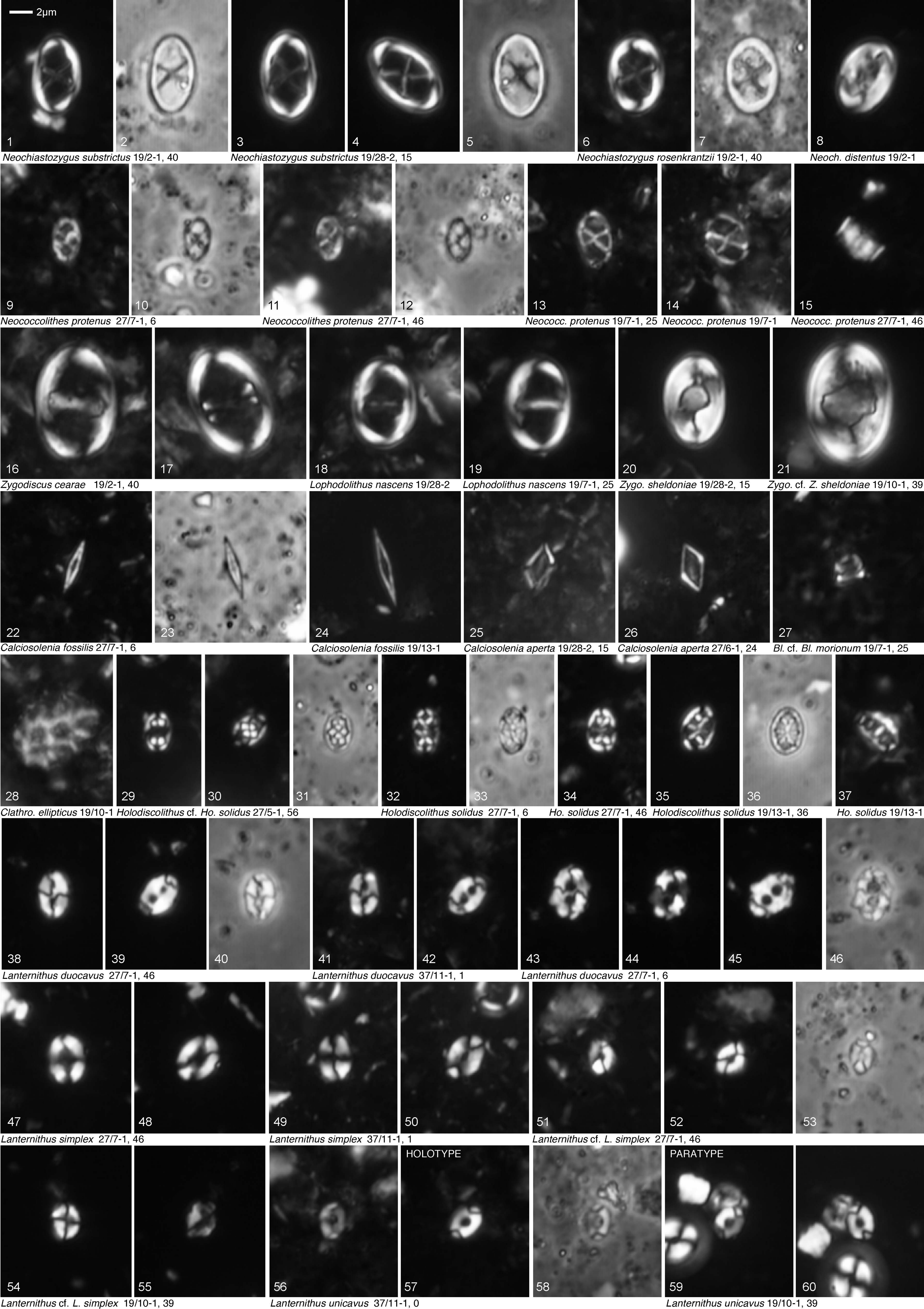
Pontosphaera veta 27/6-1, 24 *Pontosphaera veta* 37/10-1, 42 *Pontosphaera veta* 37/10-1, 42 *Pontosphaera veta* 37/10-1, 42 *Pontosphaera veta* 27/7-1, 6

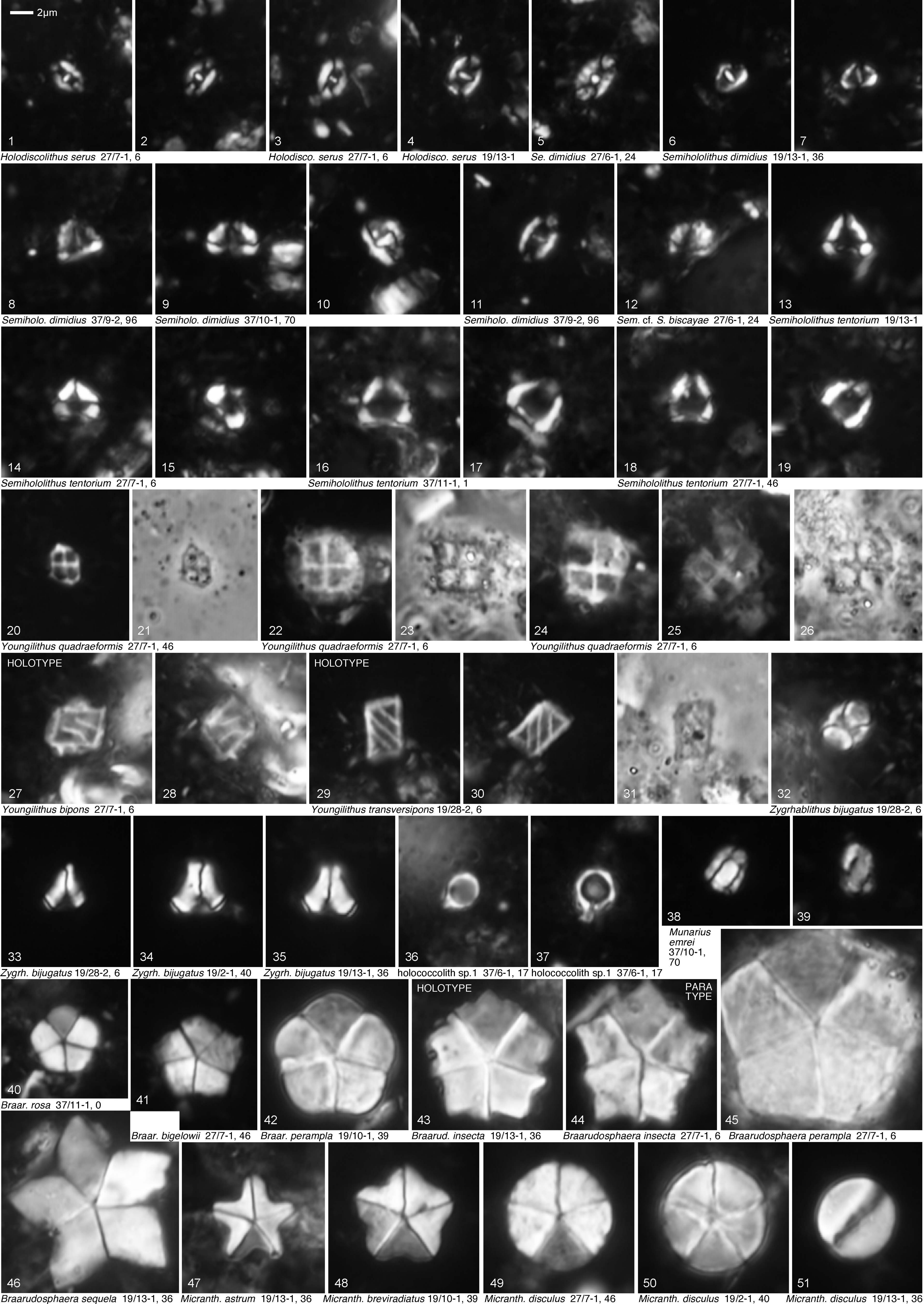


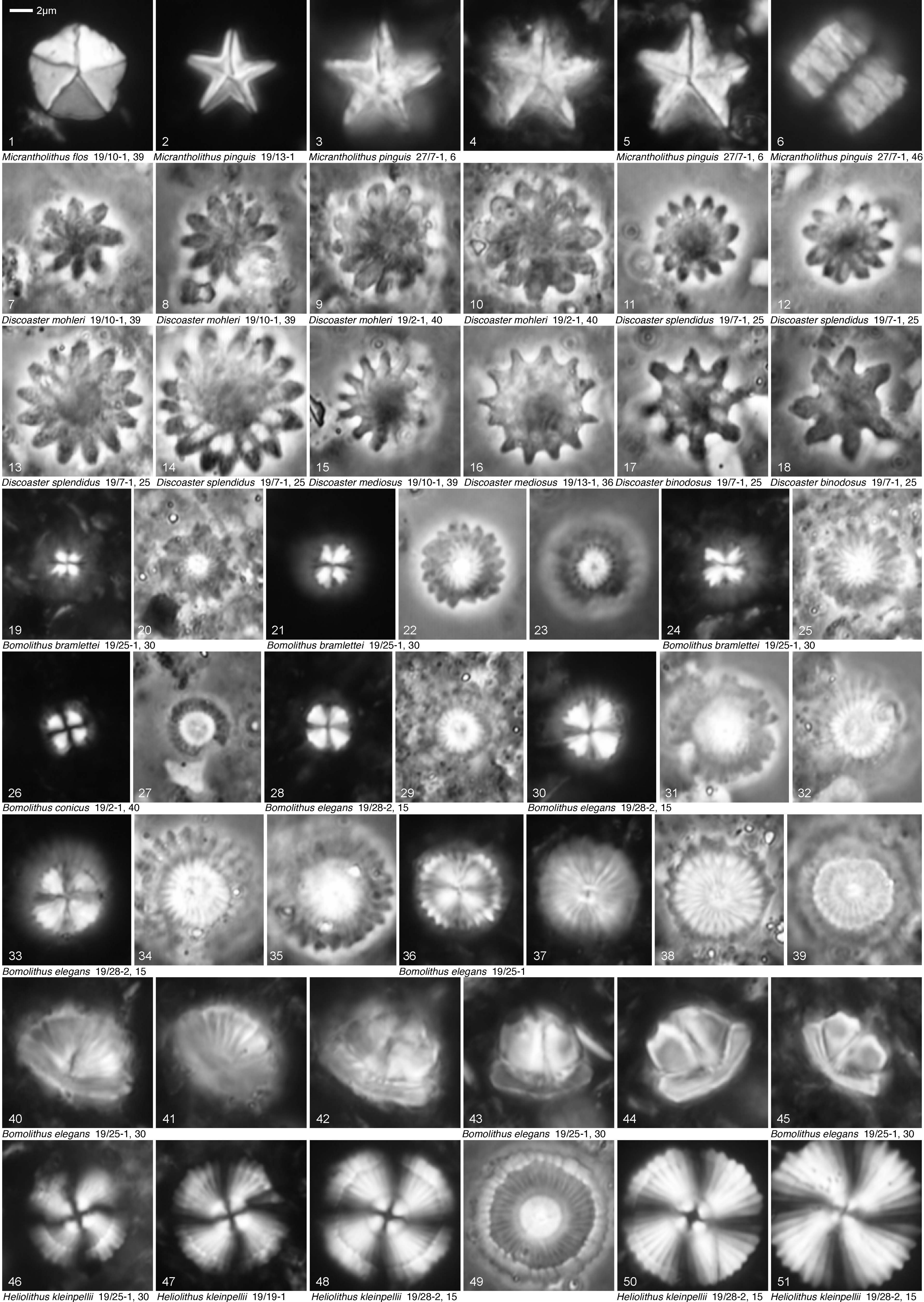
Neochiastozygus concinus 19/2-1, 40 *Neochiastozygus imbriei* 27/7-1, 46 *Neoch. imbriei* 27/7-1, 6 *Ne. imbriei* 27/7-1, 46 *Neochiastozygus imbriei* 19/7-1, 25



Neochiastozygus perfectus 37/9-2, 96 *Neochiast. junctus* 19/10-1, 39 *Neochiastozygus modestus* 27/7-1, 46 *Neochiastozygus modestus* 27/7-1, 6


2µm
Neochiastozygus substrictus 19/2-1, 40
Neochiastozygus substrictus 19/28-2, 15
Neochiastozygus rosenkrantzii 19/2-1, 40
Neoch. distentus 19/2-1
Neococcolithes protenus 27/7-1, 6
Neococcolithes protenus 27/7-1, 46
Neococc. protenus 19/7-1, 25
Neococc. protenus 19/7-1
Neococc. protenus 27/7-1, 46
Zygodiscus cearae 19/2-1, 40
Lophodolithus nascens 19/28-2
Lophodolithus nascens 19/7-1, 25
Zygo. sheldoniae 19/28-2, 15
Zygo. cf. Z. sheldoniae 19/10-1, 39
Calciosolenia fossilis 27/7-1, 6
Calciosolenia fossilis 19/13-1
Calciosolenia aperta 19/28-2, 15
Calciosolenia aperta 27/6-1, 24
Bl. cf. Bl. morionum 19/7-1, 25
Clathro. ellipticus 19/10-1
Holodiscolithus cf. Ho. solidus 27/5-1, 56
Holodiscolithus solidus 27/7-1, 6
Ho. solidus 27/7-1, 46
Holodiscolithus solidus 19/13-1, 36
Ho. solidus 19/13-1
Lanternithus duocavus 27/7-1, 46
Lanternithus duocavus 37/11-1, 1
Lanternithus duocavus 27/7-1, 6
Lanternithus simplex 27/7-1, 46
Lanternithus simplex 37/11-1, 1
Lanternithus cf. L. simplex 27/7-1, 46
Lanternithus cf. L. simplex 19/10-1, 39
Lanternithus unicavus 37/11-1, 0
HOLOTYPE
PARATYPE
Lanternithus unicavus 19/10-1, 39


2μm
HOLOTYPE
HOLOTYPE
HOLOTYPE
PARA TYPE
Holodiscolithus serus 27/7-1, 6
Holodisco. serus 27/7-1, 6
Holodisco. serus 19/13-1
Se. dimidius 27/6-1, 24
Semihololithus dimidius 19/13-1, 36
Semiholo. dimidius 37/9-2, 96
Semiholo. dimidius 37/10-1, 70
Semiholo. dimidius 37/9-2, 96
Sem. cf. S. biscayae 27/6-1, 24
Semihololithus tentorium 19/13-1
Semihololithus tentorium 27/7-1, 6
Semihololithus tentorium 37/11-1, 1
Semihololithus tentorium 27/7-1, 46
Youngilithus quadraeformis 27/7-1, 46
Youngilithus quadraeformis 27/7-1, 6
Youngilithus quadraeformis 27/7-1, 6
Youngilithus bipons 27/7-1, 6
Youngilithus transversipons 19/28-2, 6
Zygrhablithus bijugatus 19/28-2, 6
Zygrh. bijugatus 19/28-2, 6
Zygrh. bijugatus 19/2-1, 40
Zygrh. bijugatus 19/13-1, 36
holococcolith sp.1 37/6-1, 17
holococcolith sp.1 37/6-1, 17
Munarius emrei 37/10-1, 70
Braar. rosa 37/11-1, 0
Braar. bigelowii 27/7-1, 46
Braar. perampla 19/10-1, 39
Braarud. insecta 19/13-1, 36
Braarudosphaera insecta 27/7-1, 6
Braarudosphaera perampla 27/7-1, 6
Braarudosphaera sequela 19/13-1, 36
Micranth. astrum 19/13-1, 36
Micranth. breviradiatus 19/10-1, 39
Micranth. disculus 27/7-1, 46
Micranth. disculus 19/2-1, 40
Micranth. disculus 19/13-1, 36


2µm
1
Micrantholithus flos 19/10-1, 39
2
Micrantholithus pinguis 19/13-1
3
Micrantholithus pinguis 27/7-1, 6
4
5
Micrantholithus pinguis 27/7-1, 6
6
Micrantholithus pinguis 27/7-1, 46
7
Discoaster mohleri 19/10-1, 39
8
Discoaster mohleri 19/10-1, 39
9
Discoaster mohleri 19/2-1, 40
10
Discoaster mohleri 19/2-1, 40
11
Discoaster splendidus 19/7-1, 25
12
Discoaster splendidus 19/7-1, 25
13
Discoaster splendidus 19/7-1, 25
14
Discoaster splendidus 19/7-1, 25
15
Discoaster mediosus 19/10-1, 39
16
Discoaster mediosus 19/13-1, 36
17
Discoaster binodosus 19/7-1, 25
18
Discoaster binodosus 19/7-1, 25
19
20
Bomolithus bramlettei 19/25-1, 30
21
22
23
Bomolithus bramlettei 19/25-1, 30
24
25
Bomolithus bramlettei 19/25-1, 30
26
27
Bomolithus conicus 19/2-1, 40
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29
Bomolithus elegans 19/28-2, 15
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31
32
Bomolithus elegans 19/28-2, 15
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34
35
Bomolithus elegans 19/28-2, 15
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38
39
Bomolithus elegans 19/25-1
40
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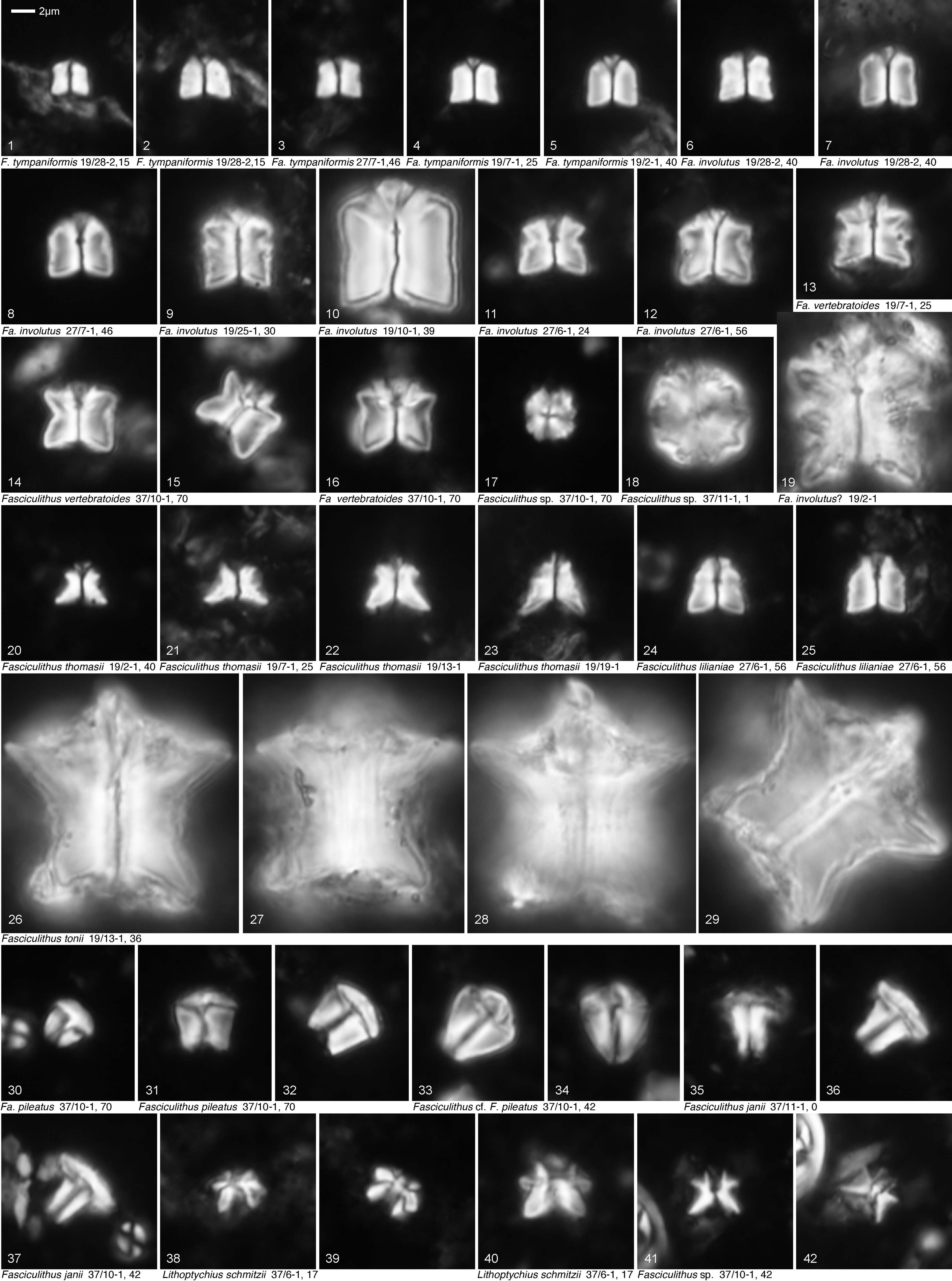
42
Bomolithus elegans 19/25-1, 30
43
44
Bomolithus elegans 19/25-1, 30
45
Bomolithus elegans 19/25-1, 30
46
Heliolithus kleinpellii 19/25-1, 30
47
Heliolithus kleinpellii 19/19-1
48
49
Heliolithus kleinpellii 19/28-2, 15
50
Heliolithus kleinpellii 19/28-2, 15
51
Heliolithus kleinpellii 19/28-2, 15



1 *F. tympaniformis* 19/28-2,15 2 *F. tympaniformis* 19/28-2,15 3 *Fa. tympaniformis* 27/7-1,46 4 *Fa. tympaniformis* 19/7-1, 25 5 *Fa. tympaniformis* 19/2-1, 40 6 *Fa. involutus* 19/28-2, 40 7 *Fa. involutus* 19/28-2, 40

8 *Fa. involutus* 27/7-1, 46 9 *Fa. involutus* 19/25-1, 30 10 *Fa. involutus* 19/10-1, 39 11 *Fa. involutus* 27/6-1, 24 12 *Fa. involutus* 27/6-1, 56 13 *Fa. vertebratoides* 19/7-1, 25

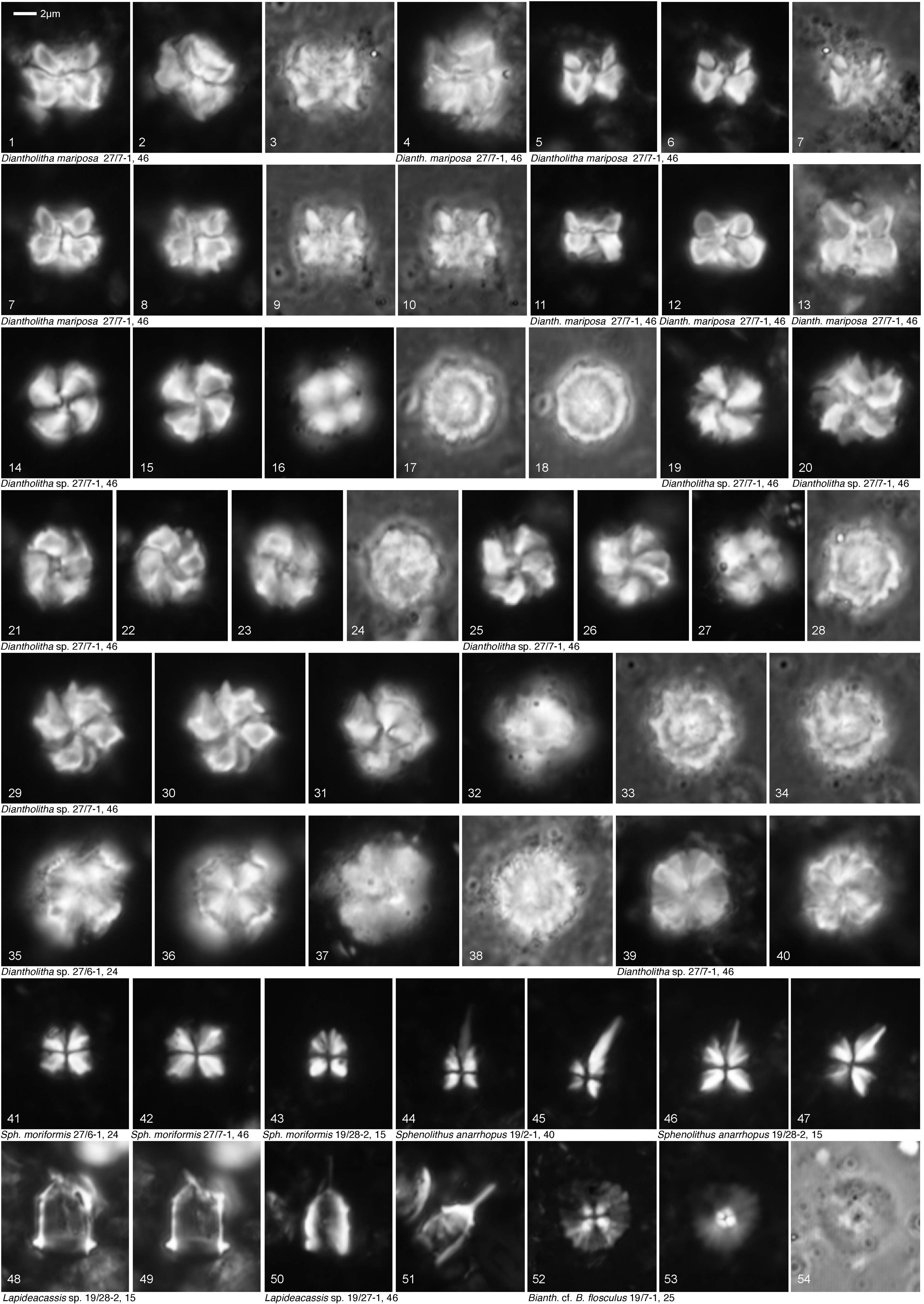
14, 15 *Fasciculithus vertebratoides* 37/10-1, 70 16 *Fa vertebratoides* 37/10-1, 70 17 *Fasciculithus* sp. 37/10-1, 70 18 *Fasciculithus* sp. 37/11-1, 1 19 *Fa. involutus*? 19/2-1

20 *Fasciculithus thomasii* 19/2-1, 40 21 *Fasciculithus thomasii* 19/7-1, 25 22 *Fasciculithus thomasii* 19/13-1 23 *Fasciculithus thomasii* 19/19-1 24 *Fasciculithus lilianiae* 27/6-1, 56 25 *Fasciculithus lilianiae* 27/6-1, 56

26–29 *Fasciculithus tonii* 19/13-1, 36

30 *Fa. pileatus* 37/10-1, 70 31, 32 *Fasciculithus pileatus* 37/10-1, 70 33, 34 *Fasciculithus* cf. *F. pileatus* 37/10-1, 42 35, 36 *Fasciculithus janii* 37/11-1, 0

37 *Fasciculithus janii* 37/10-1, 42 38, 39 *Lithoptychius schmitzii* 37/6-1, 17 40 *Lithoptychius schmitzii* 37/6-1, 17 41, 42 *Fasciculithus* sp. 37/10-1, 42


2µm
1
2
3
4
5
6
7
Diantholitha mariposa 27/7-1, 46
Dianth. mariposa 27/7-1, 46
Diantholitha mariposa 27/7-1, 46
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11
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13
Diantholitha mariposa 27/7-1, 46
Dianth. mariposa 27/7-1, 46
Dianth. mariposa 27/7-1, 46
Dianth. mariposa 27/7-1, 46
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20
Diantholitha sp. 27/7-1, 46
Diantholitha sp. 27/7-1, 46
Diantholitha sp. 27/7-1, 46
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25
26
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28
Diantholitha sp. 27/7-1, 46
Diantholitha sp. 27/7-1, 46
29
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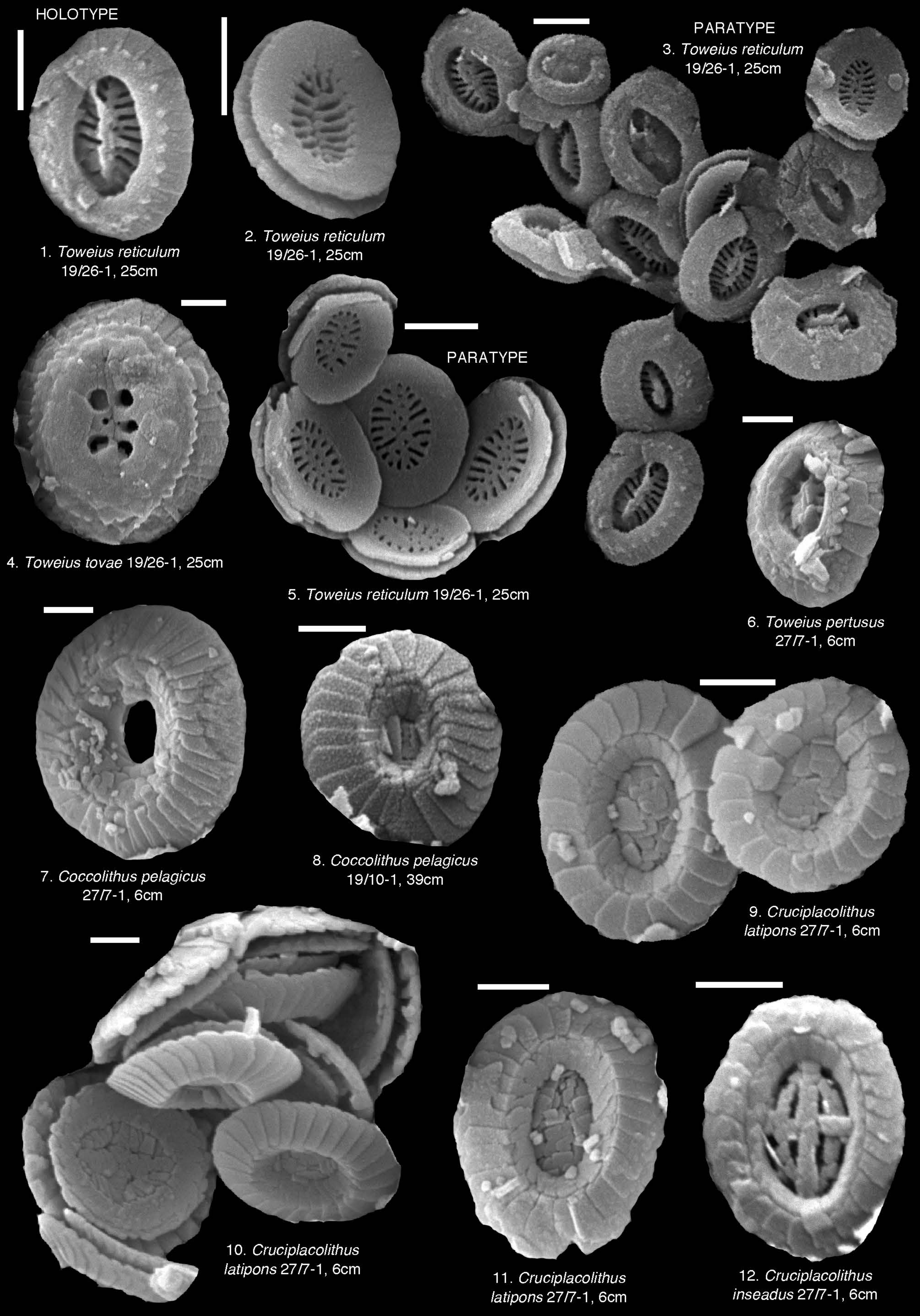
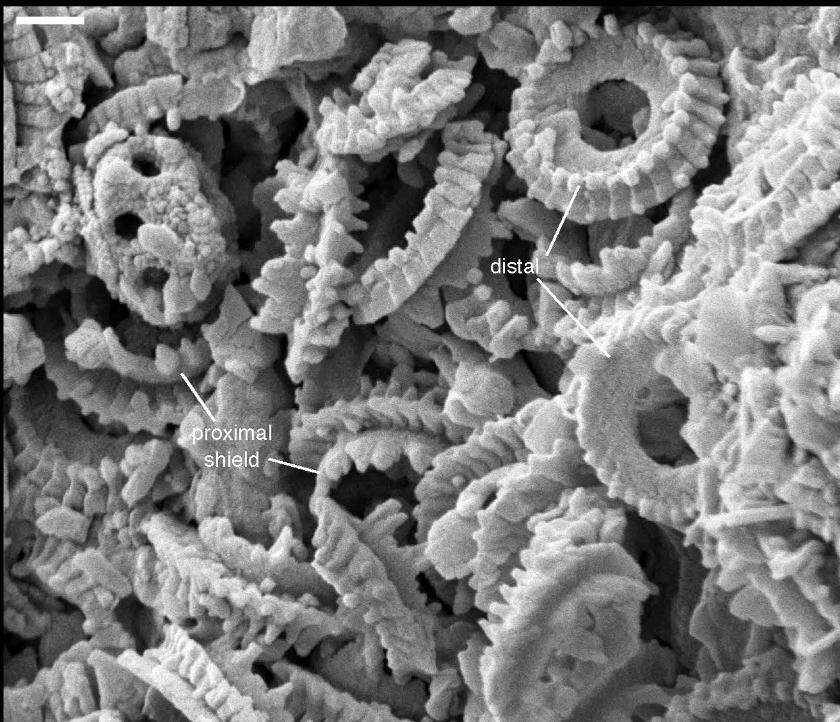
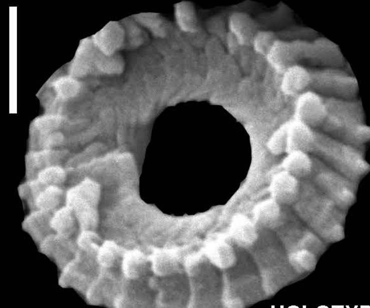
31
32
33
34
Diantholitha sp. 27/7-1, 46
35
36
37
38
39
40
Diantholitha sp. 27/6-1, 24
Diantholitha sp. 27/7-1, 46
41
42
43
44
45
46
47
Sph. moriformis 27/6-1, 24
Sph. moriformis 27/7-1, 46
Sph. moriformis 19/28-2, 15
Sphenolithus anarrhopus 19/2-1, 40
Sphenolithus anarrhopus 19/28-2, 15
48
49
50
51
52
53
54
Lapideacassis sp. 19/28-2, 15
Lapideacassis sp. 19/27-1, 46
Bianth. cf. B. flosculus 19/7-1, 25


HOLOTYPE
1. Toweius reticulum 19/26-1, 25cm
2. Toweius reticulum 19/26-1, 25cm
PARATYPE
3. Toweius reticulum 19/26-1, 25cm
4. Toweius tovae 19/26-1, 25cm
PARATYPE
5. Toweius reticulum 19/26-1, 25cm
6. Toweius pertusus 27/7-1, 6cm
7. Coccolithus pelagicus 27/7-1, 6cm
8. Coccolithus pelagicus 19/10-1, 39cm
9. Cruciplacolithus latipons 27/7-1, 6cm
10. Cruciplacolithus latipons 27/7-1, 6cm
11. Cruciplacolithus latipons 27/7-1, 6cm
12. Cruciplacolithus inseadus 27/7-1, 6cm

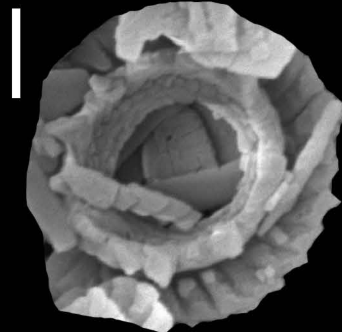


1. *Ericsonia monilis* - collapsed coccosphere 27/7-1, 6cm **PARATYPE**

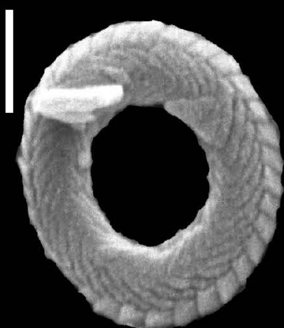


HOLOTYPE

2. *Ericsonia monilis* 3.1µm distal
27/7-1, 6cm



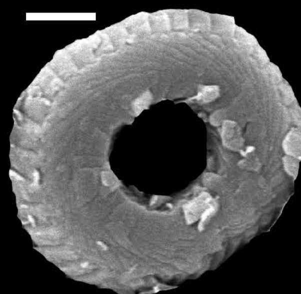
3. *Ericsonia monilis* proximal
27/7-1, 6cm



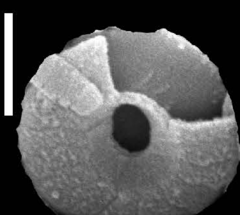
4. *Ericsonia orbis* 2.9µm
distal 27/7-1, 6cm

5. *Ericsonia orbis* 4.1µm
distal 27/7-1, 6cm

6. *Ericsonia orbis* 2.9µm
distal 27/7-1, 6cm

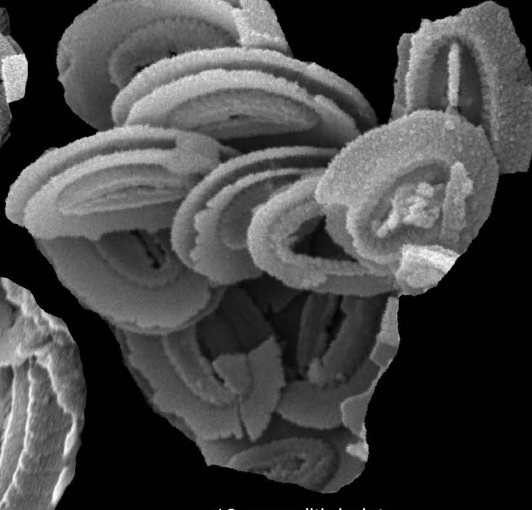


7. *Ericsonia subpertusa* distal
27/7-1, 6cm

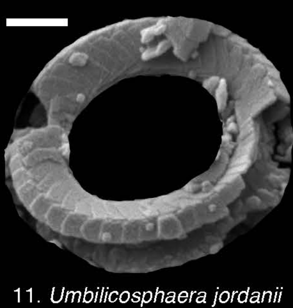


8. *Calcidiscus* sp.
19/26-1, 25cm

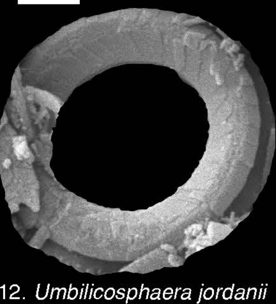
9. *Hayaster perplexus*
19/26-1, 25cm



10. coccolith indet.
19/26-1, 25cm



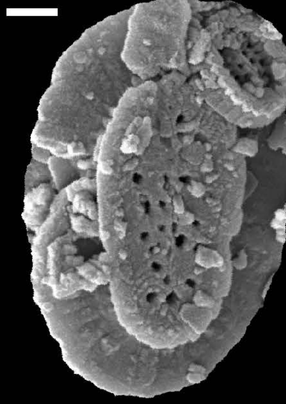
11. *Umbilicosphaera jordanii*
27/7-1, 6cm



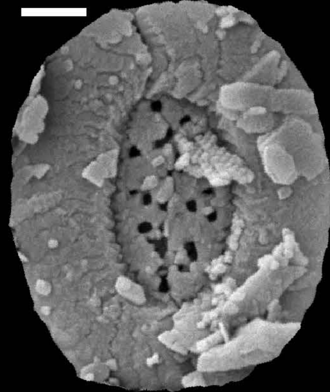
12. *Umbilicosphaera jordanii*
19/26-1, 25cm

13. *Craticullithus cassus*
19/10-1, 39cm

1. *Ellipsolithus pumex*
27/7-1, 6cm **PARATYPE**



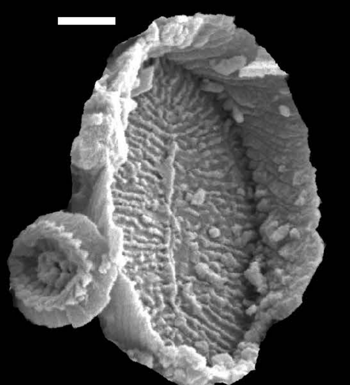
2. *Ellipsolithus pumex*
27/7-1, 6cm



3. *Ellipsolithus pumex*
27/7-1, 6cm

4. *Ellipsolithus pumex*
27/7-1, 6cm

5. coccolith indet. 19/26-1, 25cm



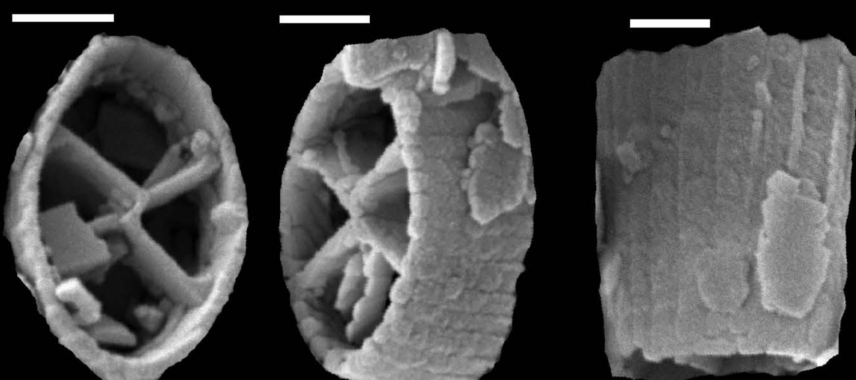
6. *Pontosphaera plana*
27/7-1, 6cm

7. *Pontosphaera plana*
27/7-1, 6cm

PARATYPE

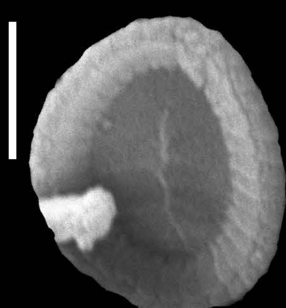
8. *Pontosphaera* vetus
19/26-1, 25cm

9. *Neochiastozygus modestus*
27/7-1, 6cm

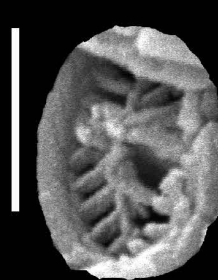


10. *Neococcolithes protenus* 27/7-1, 6cm

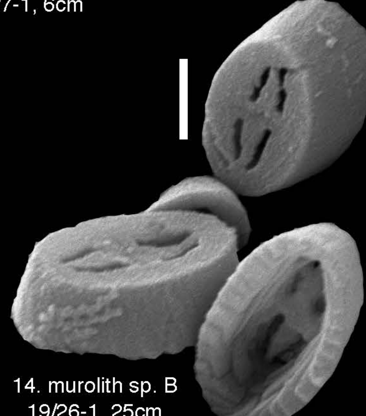
11. placolith indet.
19/26-1, 25cm



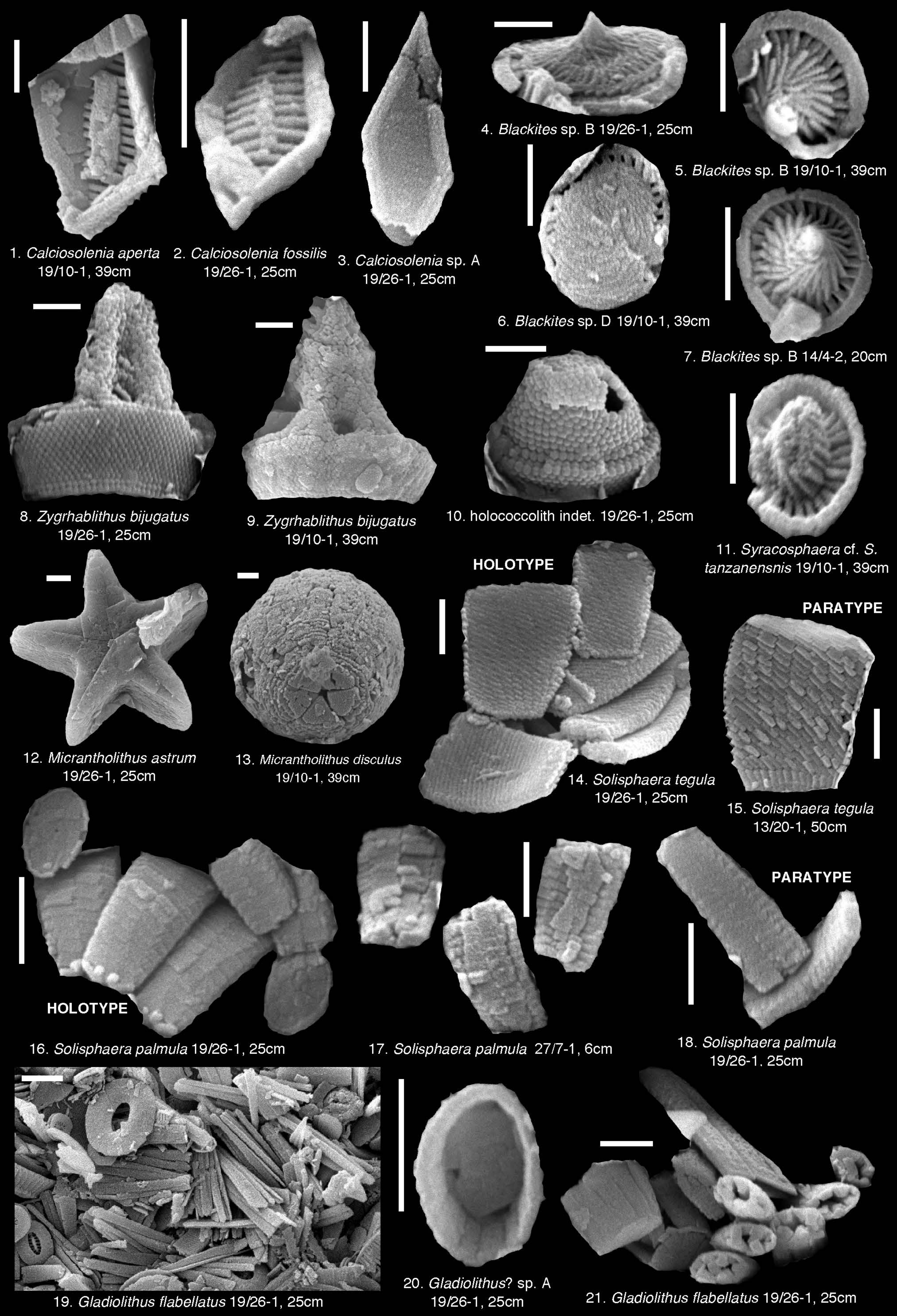
12. coccolith indet.
19/26-1, 25cm



13. murolith sp. A
19/26-1, 25cm



14. murolith sp. B
19/26-1, 25cm



1. *Calciosolenia aperta* 19/10-1, 39cm
2. *Calciosolenia fossilis* 19/26-1, 25cm
3. *Calciosolenia* sp. A 19/26-1, 25cm
4. *Blackites* sp. B 19/26-1, 25cm
5. *Blackites* sp. B 19/10-1, 39cm
6. *Blackites* sp. D 19/10-1, 39cm
7. *Blackites* sp. B 14/4-2, 20cm
8. *Zygrhablithus bijugatus* 19/26-1, 25cm
9. *Zygrhablithus bijugatus* 19/10-1, 39cm
10. holococcolith indet. 19/26-1, 25cm
11. *Syracosphaera* cf. *S. tanzanensnis* 19/10-1, 39cm
12. *Micrantholithus astrum* 19/26-1, 25cm
13. *Micrantholithus disculus* 19/10-1, 39cm
14. *Solisphaera tegula* 19/26-1, 25cm
15. *Solisphaera tegula* 13/20-1, 50cm
16. *Solisphaera palmula* 19/26-1, 25cm
17. *Solisphaera palmula* 27/7-1, 6cm
18. *Solisphaera palmula* 19/26-1. 25cm
19. *Gladiolithus flabellatus* 19/26-1, 25cm
20. *Gladiolithus*? sp. A 19/26-1, 25cm
21. *Gladiolithus flabellatus* 19/26-1, 25cm