

New and intriguing calcareous nannofossils from the Turonian (Upper Cretaceous) of Tanzania

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Abstract

The preservation of exceptionally well-preserved, primary associations of calcareous nannofossils on lamina surfaces of shallowly-buried, uncemented, clay-rich Turonian sediments of coastal Tanzania has enabled us to document several intriguing new morphologies using the scanning electron microscope (SEM). Based on our new observations, we describe a new genus, *Jimenezberrocosoia*, and six new species, *J. birchiae*, *Ellipsolithus linnertii*, *Petrarhabdus? kirenii*, *Braarudosphaera wendleriae*, *Nannoconus funiculus* and *Kokia kayae*. We have also made two new combinations, *Jimenezberrocosoia bosunensis* (Jeremiah, 2001) and *Nannoconus nicholasii* (Lees, 2007), and emended the Order Braarudosphaerales to include the Nannoconaceae. Most of the taxa are illustrated with both SEM and light microscope images. The presence of *Ellipsolithus* in these Cretaceous sediments greatly extends the range of this formerly Cenozoic-restricted taxon.

Keywords Upper Cretaceous, Turonian, Tanzania Drilling Project, calcareous nannofossil taxonomy, Nannoconaceae, Braarudosphaeraceae, Braarudosphaerales

1. Introduction

Phase II of the Tanzania Drilling Project (TDP, 2007-2009) was aimed at intervals of specific climate change interest in the Upper Cretaceous (primarily Oceanic Anoxic Event 2 and the Cretaceous/Palaeogene boundary) preserved in shallowly-buried, clay-rich sediments that were known, from TDP Phase I, to frequently host the pristinely-preserved foraminifera required for best-quality palaeoenvironmental stable-isotope geochemistry (Pearson *et al.*, 2001; Bown *et al.*, 2008). Whilst these targets were elusive, the three drilling seasons *did* result in 18 Upper Cretaceous holes. These, supplemented with three holes drilled during Phase I, provide several hundred metres of a very well-preserved and expanded record of the entire Upper Cretaceous,

albeit with significant stratigraphic gaps. Preliminary reports on all of these holes have been published (Pearson *et al.*, 2004, 2006; Nicholas *et al.*, 2006; Jiménez Berrocoso *et al.*, 2010, 2012, 2015) and some new Upper Cretaceous nannofossil taxonomy from the Phase I holes was presented in Lees (2007). A high-resolution nannofossil biostratigraphic study of a composite Upper Cretaceous section has now been completed (Lees, in prep.) and this requires description and clarification of several more taxa.

Study of these Cretaceous Tanzanian sediments has revealed single-sample nannofossil assemblages with species richness values equivalent to 3Myr-binned global tallies of species richness (Bown *et al.*, 2004), and very high proportions of small and delicate taxa that are not a feature of assemblages elsewhere (Bown *et al.*, 2008). Consequently, these assemblages are very important in expanding the record, and our understanding, of Cretaceous greenhouse sea-surface environments. To help with describing the new taxa identified by light-microscope (LM) study, some of which are too small to adequately describe based on LM images alone, and some of which had intriguing morphologies that required scanning electron microscope (SEM) observation, we conducted an extensive SEM study, results from a portion of which are presented here.

Here, we describe a new genus, six new species, and make two new combinations - all taxa found in the Turonian and many showing distinctive morphologies not previously seen in Cretaceous nannofossils.

2. Material and methods

The Albian through Coniacian Lindi Formation (defined in Jiménez Berrocoso *et al.*, 2015) comprises interbedded dark grey claystones and siltstones, with occasional thin sandstone beds, deposited on the outer shelf to upper slope, at water-depths of 300-500m. This formation grades into the Nangurukuru Formation (Santonian-Maastrichtian), dominated by paler claystones with a greater CaCO₃ content and exhibiting evidence of bioturbation (Jiménez Berrocoso *et al.*, 2010, 2012, 2015). The Tanzanian nannofossils (and microfossils) that display exceptional preservation are preserved in finely-laminated, clay-dominated intervals of the Lindi Formation. Based on data from the LM study (Lees, in prep.), we focused the SEM study on such samples from TDP Sites 31 (UC6a to UC9b, lowermost to Upper Turonian) and 36 (UC6b, lowermost Turonian). Figure 1 shows these site locations. We have supplemented the SEM images with LM images from other sites included in the Lees study (in prep.; see Table 1).

LM images were taken from simple smears of sediment on a glass coverslip, mobilised with two drops of deionised water using a flat-sided toothpick, flash-dried on a hotplate and mounted on a glass slide using Norland optical adhesive, which was cured in UV light (after Bown & Young, 1998). For the SEM images, unadulterated chips of sediment, broken along lamina surfaces, were mounted on SEM stubs, with the freshly-broken lamina facing upwards on the stub (after Lees *et al.*, 2004). Sample notation is TDP Site number/core (3m lengths)-section (1m subdivisions of each core), depth in section in cm.

The observation of broken rock surfaces has proved to be a particularly productive and revealing method in these sediments, albeit very time-consuming to find nanofossil-rich patches. It particularly allows the imaging of *in situ* nanofossil concentrations and associations on μm -scale lamina surfaces, undisturbed by metazoan bioturbation, and thus conserving collapsed coccospheres and very fragile taxa that we deduce are destroyed during even the most conservative LM slide preparation.

3. Results

Only samples used in the SEM study are described here; further samples from the high-resolution LM study are described in Lees (in prep.). Samples TDP31/41-1, 20cm (UC6b-7, Lower Turonian) and TDP31/63-1, 13cm (UC6b, Lower Turonian) were qualitatively evaluated as having relatively good preservation and moderate to high abundance in the LM. TDP36/5-1, 26cm and TDP36/11-1, 1cm (UC6b, Lower Turonian) exhibit good preservation and low to moderate abundance in the LM. The nanofossils are significantly subordinate to clay in all of these samples.

The TDP31 LM samples have species richness values of *c.*100-135, whilst values of *c.*100-110 were recorded in the TDP36 slides; we believe these are higher diversity values than seen geographically anywhere else in the Turonian. The quality of preservation is demonstrated not only by this enhanced species richness, but also by the common presence of small ($<3\mu\text{m}$, especially *Biscutum* and *Zeugrhabdotus*) and delicate (especially *Calciosolenia*, *Corolithion*, *Stradnerlithus*, *Truncatoscapus* and holococcoliths) coccoliths, complete coccospheres, frangible central structures, and other taxa that are prone to post-mortem dissolution.

The exquisite nature of the preservation only becomes fully apparent when freshly-exposed lamina surfaces are viewed using the SEM. This methodology circumvents the dissolution and/or fragmentation of some of the very small and/or very fragile taxa (*e.g.* those

mentioned above) that we believe occurs during wet-processing preparation techniques. Although this SEM method is time-consuming and does not suit all sample types, we have consistently achieved good results from the Palaeogene claystones of the upper Kilwa Group (*e.g.* Bown *et al.*, 2008, 2009; Bown, 2010). Here, we have found comparable concentrations in the considerably older Cretaceous sediments and have encountered previously unseen diversity. The nanofossils occur disaggregated and dispersed throughout the sediment fabric, and only rarely are found in concentrations that most likely represent undisturbed marine-snow aggregates or fecal pellets. These concentrations are uncemented and generally show little sign of any modification by overgrowth or dissolution. We consider these concentrations to represent ‘snapshots’ of *in situ* nanoplankton populations, which retain original diversities and community structure, relatively unaffected by dissolution or diagenesis.

The SEM associations have relatively typical, putatively oligotrophic, Late Cretaceous community structure, with common *Biscutum*, *Prediscosphaera*, *Retecapsa*, *Staurolithites* and *Zeughrabdotos*. Other aspects of the assemblages are less typical, with the consistent presence of fragile taxa, such as diverse holococcoliths, and abundant, minute biscutateans, zeughrabdotos and stradnerlithids. We also encountered previously unseen diversity, especially in the small to very small coccolith fraction, and conspicuously abundant truncatoscapheids. The purpose of this, and following reports, is to document some of the more unusual taxonomic diversity seen in the SEM, however, we are also conducting a palaeoecological study to document and speculate on the associations of these taxa.

4. Systematic palaeontology

Here, we report on some new taxa and clarify two previously-published species. All of these taxa were first observed in the LM study (Lees, in prep.), but some of them were too small and/or crystallographically complex to describe from LM observations alone. Our SEM observations provide better insight into these forms, and showcase intriguing morphologies that have not been previously seen in the Upper Cretaceous. The descriptive terminology follows the guidelines of Young *et al.* (1997) and the higher taxonomy essentially follows Bown & Young (1997). Only bibliographic references not included in Perch-Nielsen (1985) or Bown (1998) are included in the reference list. The following abbreviations are used: XPL - cross-polarised light, PPL – plane-polarised light, PC – phase-contrast illumination, L – length, W – width, D – diameter. Type images are stored in the Department of Earth Sciences, University College London.

The SEM images are reproduced at variable magnifications, but a 1 μ m scale-bar is provided beside each image. The LM images were taken on two different microscopes, each using different, but consistent, magnification. These are reproduced at that consistent-per-microscope magnification, with a 2 μ m scale-bar beside each specimen.

4.1.1 Placolith coccoliths

Order PODORHABDALES Rood *et al.*, 1971 emend. Bown, 1987

Family BISCUTACEAE Black, 1971

Jimenezberrocosoia gen. nov.

Type species: *Jimenezberrocosoia birchiae* gen. et sp. nov. **Derivation of name:** After Dr. Álvaro Jiménez Berrocoso, Phase II TDP team sedimentologist and geochemist. **Diagnosis:** SEM - biscutatean placolith coccoliths with slits between the elements of the distal shield. The narrow to moderately wide, open, elliptical central-areas are spanned by distinct structures, comprising an axial cross and accessory bars. The proximal shield comprises a rim of elongated, widely-spaced elements radiating from the central tube-cycle. **Remarks:** Slits between shield elements is a very rare morphological feature in the history of coccolithophores, but *is* a characteristic of the most common living taxon, *Emiliana*. We do not consider the slits in *Jimenezberrocosoia* to be a preservational (dissolution) feature, as (1) all of our specimens, from different samples and ages, exhibit these, and they are uniform in length and evenly distributed in each specimen. The effects of dissolution would be less regular and would include dissolution around the rim, causing a ragged outline; (2) no other taxa occurring in the same samples, including other biscutateans, display this feature; (3) the presence of very delicate taxa, such as *Stradnerlithus* and intact holococcoliths, in association with this genus suggest post-mortem dissolution was not active in the vicinity of these assemblages; and (4) we have found these in the SEM in at least one other location with good to exceptional preservation. This new genus has central-area features similar to certain species placed in the biscutatean genus *Sollasites* Black, 1967, but is distinct from *Sollasites* because of the distinctive rim slits in the new genus (and see further discussion on the species, below).

Jimenezberrocosoia birchiae gen. et sp. nov.

Pl.1, figs 1-4, 6, 9, ?11. **Derivation of name:** After Dr. Heather Birch, Cenozoic planktonic foram

specialist on the Phase II TDP team. **Diagnosis:** SEM – very small to small *Jimenezberrocosoia* coccoliths with a broadly elliptical outline, usually relatively long slits between the elements of the distal shield and a very constricted central-area, with a diameter of less than half the width of the rim, spanned by an axial cross that is surrounded by a single set of concentric bars (Pl.1, fig.6). The central structure is attached to the rim at the long- and short-axis points. A short spine sits at the centre of the cross. The elements of the proximal shield are thin and widely-spaced, radiating from the central tube-cycle (Pl.1, fig.9). The ends of the arms of the cross structure can be seen to attach to this tube-cycle, proximally. **Remarks:** The small size of these coccoliths ($\sim 3\mu\text{m}$ or less) has precluded us from unequivocally identifying this species in the LM so far. We have found specimens of this species in SEM samples from Blake Nose, in a similarly clay-rich lithology. **Holotype:** Pl.1, fig.6. **Dimensions:** L = $3.5\mu\text{m}$, W = $3.0\mu\text{m}$. **Paratypes:** Pl.1, figs 4, 9. **Type locality:** TDP Site 31, WNW of main road, SW of Lindi, coastal Tanzania. **Type level:** TDP31/41-1, 20cm, Lower Turonian, UC6b-UC7. **Occurrence:** TDP Sites 31, 36; Lower Turonian; UC6b-UC7; Blake Nose, NW Atlantic Ocean, Ocean Drilling Program Site 1052; Upper Albian; UC0a.

Jimenezberrocosoia bosunensis (Jeremiah, 2001) emend et comb. nov.

Basionym: *Crucibiscutum bosunensis* Jeremiah, 2001, p.73, pl.1, figs 7 (holotype), 8. Jeremiah, J. 2001. A Lower Cretaceous nannofossil zonation for the North Sea Basin. *Journal of Micropalaeontology*, **20**: 45-80.

2007 *Crucibiscutum salebrosum*? (Black, 1971) Jakubowski, 1986; Lees, p.44, pl.5, figs 24-31. Pl.1, figs 5, 7, 8, 10, 12, 13. **Remarks:** Lees (2007) questionably identified LM images of this form as *Crucibiscutum salebrosum*, which, based on Black's holotype (SEM of proximal view), has a central cross that almost fills the central-area and comprises four almost equidimensional bars. Unfortunately, Black (1971) did not provide any LM images and so later reports of *C. salebrosum* have depended on LM interpretations of that holotype; however, these seem to show that the central cross is entirely birefringent (e.g. Bown *et al.*, 1998, pl.10, fig.25). Whilst Jeremiah (2001) admitted that he was essentially using stratigraphic non-contiguity to distinguish between his new *C. bosunensis* and *C. salebrosum*, his LM holotype actually shows a distinctly longer, dark axial bar, with the shorter short-axis bars being highly birefringent when rotated. So, the Lees (2007) images actually conform to *bosunensis*, in terms of overall XPL view, size and central-area proportions.

On closer inspection, our LM images show that our forms have *Jimenezberrocosoia*-style rim-

slits, especially visible when viewed in PC (Pl.1, fig.7) or PPL (Pl.1, figs 12, 13). We contend that our LM images of *bosunensis* conform to the SEM images in Pl.1, figs 5 and 10, and that these are simply well-preserved forms of *bosunensis*. Thus, we have placed *bosunensis* into

Jimenezberrocosoia. **Emended description:** LM/SEM - broadly elliptical, small to medium-sized (~4-6 μ m long) *Jimenezberrocosoia* coccoliths; rim dark in XPL, with bright inner cycle; relatively short slits between elements of distal shield particularly visible in PPL (may not be visible in less well-preserved specimens); moderately wide, open, elongate-elliptical central-area (approximately equal to width of rim) spanned by axial cross-bars, long-axis bar being sub-rhomboidal in centre, but thinning into straight ends that attach to inner tube-cycle, surrounded by a single set of concentric bars (Pl.1, fig.10; note that concentric bars visible in SEM images are not particularly visible in any of our LM images.); short, straight short-axis bars appear bright at 45° rotation, whilst long-axis bar goes into extinction. Proximal view shows again rim composed of elongated, widely-spaced elements and central cross structure attached to inner tube-cycle, proximally (Pl.1, fig.5). **Differentiation:** This species is distinct from *J. birchiae* because the rim slits in *bosunensis* appear to be relatively shorter, the central-area is relatively wider, the central cross is constructed of different-shaped bars, and *birchiae* bears a small spine; *bosunensis* is also larger, being ~4-6 μ m, as opposed to 3 μ m or less (*birchiae*). **Occurrence:** TDP Sites 15, 22, 26, 30, 31, 33, 34, 36, 39; Middle Cenomanian-Coniacian; UC3a/b-UC11.

Discussion: Although the basic rim structure of *Jimenezberrocosoia* is biscutatean, it differs from all other Mesozoic rims in possessing slits between the distal shield elements and in having a proximal shield of narrow, widely-spaced elements. It is possible that the distal-shield slits could overgrow in less well-preserved specimens, and the central structure in *Jimenezberrocosoia* is reminiscent of that in the biscutatean *Sollasites lowei* (Bukry, 1969) Rood *et al.*, 1971 - an axial cross surrounded by a set of concentric bars, that structure also being anchored to the rim at the axial points. However, although the holotype of *S. lowei* shows calcite overgrowth (Bukry, 1969, pl.22, fig.6), other SEM images of better-preserved *S. lowei* specimens (*e.g.* Bown & Cooper, 1998, pl.4.5, fig.8) clearly show no evidence of overgrown rim slits. Furthermore, the central-areas in both *J. birchiae* and *J. bosunensis* are proportionally, respectively, much smaller and smaller than in the holotype of *S. lowei*, in which the central-area is twice as wide as the rim. The bars are straight and all of equal thickness in *S. lowei*, whereas the axial bar in *J. bosunensis* is sub-rhomboidal. There are other iterations of this central structure in the Mesozoic: Jurassic species

with similar central structures include forms with rims that do not appear to be biscutatean: the Oxfordian holotype of *S. concentricus* Rood *et al.*, 1971 (proximal view) appears to have a loxolith rim, for example.

Crucibiscutum is another biscutatean form with an axial cross (*e.g.* *C. salebrosum* (Black, 1971) Jakubowski, 1986 as illustrated in Bown *et al.*, 1998, pl.5.3, fig.13), but this genus does not have slits in the rim, nor concentric bars.

Family **PREDISCOSPHAERACEAE** Rood *et al.*, 1971

Petrarhabdus? kirenii

Pl.2, figs 11-14. **Derivation of name:** After Kiren MacLeod, son of the TDP Phase II team co-chief and principal geochemist. **Diagnosis:** A very small to small, dark form comprising a single cycle of four radial, triangular/trapezoid elements of equal size. At the centre, there is usually a very small structure composed of four equidimensional crystallites. **Remarks:** As yet, we have not seen this taxon in the SEM. This is a very distinctive form, but is possibly the spine-top of an as yet undescribed coccolith. We tentatively place this in *Petrarhabdus* until we have more information, because the spine-top in *Petrarhabdus* is similarly distinctive and composed of four sub-triangular elements. However, *Petrarhabdus* is much larger and more robust-looking, with high yellow birefringence, and usually attached to a coccolith of equivalent or larger dimensions that is easily visible in the LM. **Holotype:** Pl.2, fig.13. **Dimensions:** L = 2.3 μ m, W = 2.3 μ m. **Paratype:** Pl.2, fig.11. **Type locality:** TDP Site 39, NW of Nangurukuru junction, SW of main road, coastal Tanzania. **Type level:** TDP39/32-1, 0cm, UC10, Coniacian. **Occurrence:** TDP Sites 26, 29, 31, 33, 34, 36, 37, 38, 39; Middle Cenomanian-Coniacian, ?Lower Maastrichtian; UC3a/b-UC11, ?UC19.

4.1.2 *Incertae sedis* placolith coccoliths

Ellipsolithus Sullivan, 1964

Remarks: *Ellipsolithus*-type coccoliths have previously been described from the Palaeogene only, and have a structure that is quite distinct from the principal Cenozoic placolith orders, Coccolithales and Isochrysidales. They are unlike any previously-described Mesozoic taxa. These elongate, rounded-oblong placoliths comprise unicyclic distal shields built of numerous (>50) narrow elements joined along 'frilly' sutures. In the Palaeogene species, the central-area is filled

by an either perforate (*E. anadoluensis*: Pl. 2, fig.4) or imperforate (*E. macellus*) plate and may have additional bars (*E. distichus*). *Ellipsolithus anadoluensis* has an elevated distal rim and is frequently observed in side view in the LM. The presence of specimens closely resembling *Ellipsolithus* in sediments as old as the Cenomanian, some *c.*30Myr older than any previous records, is either because these older coccoliths are homeomorphs of the younger taxon, or these early forms are fragile and so not typically preserved in the fossil record. We consider the latter explanation to be the most likely, because the exceptional preservation in these Tanzanian sediments has already revealed similarly striking range extensions in other coccolithophore groups, *e.g.* *Gladiolithus*, *Algirosphaera*, *Acanthoica*, *Umbilicosphaera*, *etc.* (Bown *et al.*, 2007, 2008, 2009), and because the new Cretaceous species has a recorded range at least up into the Lower Maastrichtian. In addition, these Cenomanian-Maastrichtian *Ellipsolithus* specimens are rare and their LM appearance, in less well-preserved sediments, may be similar to other taxa, especially elongate rhagodiscids, such as *Rhagodiscus angustus* and *R. reniformis*, and so they may have been overlooked or misidentified. Both LM and SEM observations show that the thin shields of the Cretaceous *Ellipsolithuses* are easily damaged, or broken off completely, leaving the bright tube-cycle (viewed in XPL) looking particularly like an *R. angustus* rim. The older specimens of *Ellipsolithus* in the Palaeogene part of their range are similarly sensitive to preservation (*e.g.* Agnini *et al.*, 2007).

Ellipsolithus anadoluensis Varol, 1989

Pl.2, fig.4

Ellipsolithus linnertii sp. nov.

Pl. 2, figs 1-3, 5–10. **Derivation of name:** After Dr. Christian Linnert, Upper Cretaceous nannofossil specialist. **Diagnosis:** SEM - medium, narrowly-elliptical to parallel-sided *Ellipsolithus* with an elevated distal rim and relatively wide central-area (similar to, or greater than, the rim width) filled with an imperforate plate that bears two depressions along the long axis. In XPL, the tube cycle shows the highest (white) interference colour, with the shields and central-area plate typically having a low, grey interference colour. **Differentiation:** Distinguished from other *Ellipsolithus* species by a combination of the elevated distal rim, imperforate central-area plate with depressions, and bright tube-cycle in XPL. The Paleocene *E. anadoluensis* is shown to illustrate the generic similarities between it and the Cretaceous forms. *E. linnertii* is

distinct from *Rhagodiscus angustus*, which has a murolith rim with a sharp, highly-birefringent outline, whereas *E. linnertii* has a distinct, ragged grey rim visible outside of the bright inner cycle. **Remarks:** We potentially illustrate two forms here: *linnertii* having a shallower rim and depressions in the central-area, the other having a more elevated rim (*e.g.* Pl.2, fig.2) and potentially no central-area depressions, although it is impossible to really see if this is the case, because of the calcite rhombs obscuring the central-area. **Holotype:** Pl.2, fig.1. **Dimensions:** L = 6.4 μ m, W = 4.3 μ m. **Paratypes:** Pl.2, figs 3, 8. **Type locality:** TDP Site 31, WNW of main road, SW of Lindi, coastal Tanzania. **Type level:** TDP31/63-1, 13cm, UC6b, Lower Turonian. **Occurrence:** TDP Sites 26, 31, 36, 37, 39 and Shuqualak, Mississippi, USA; Middle Cenomanian-Lower Maastrichtian; UC3b-UC20a^{TP}.

4.2.1 Haptophyte nannoliths

Order BRAARUDOSPHERALES Aubry, 2013 emend

Emended diagnosis: Coccolithophores and extinct nannofossils that produce nannoliths in one life-cycle stage that are formed from multiple layers of thin elements. Typically, the nannoliths are heavily calcified, pentagonal to circular, and range from relatively flat to very tall (higher than wide). The elements from which the nannolith is constructed are thin and flat, relatively equidimensional, triangular or square to trapezoid, but sometimes with scalloped outer edges, and they either abut (as in the Braarudosphaeraceae), or overlap each other (as in the Nannoconaceae).

Remarks: We have emended the order here to allow inclusion of the extinct nannofossil group, the nannoconids. The inference of a close phylogenetic relationship between these and the braarudosphaerids is based on a series of shared and unusual characters that include morphology (layered/laminated liths), crystallography (tangential), ecology (typically neritic) and geological history (similar Jurassic/Cretaceous boundary interval origination times).

Both Braarudosphaeraceae and Nannoconaceae nannoliths are composed of elements stacked on top of each other in laminae or layers, with or without imbrication. The similarity between braarudosphaerid and nannoconid elements, highlighted by the taxa described below, is strongly suggestive of an evolutionary link between these two taxa. In the Braarudosphaeraceae, each nannolith comprises five segments formed from stacks of non-imbricating laminae/elements (*e.g.* Young *et al.*, 1997), whereas in the Nannoconaceae, each nannolith is typically formed of numerous stacked, *imbricating* elements, although in *Nannoconus funiculus* sp. nov., this number may also be five at its

base. The evolutionary relationship is further supported by shared, atypical palaeoecology - both groups typified by neritic distribution (*e.g.* Roth & Krumbach, 1986; Street & Bown, 2000; Bown, 2005; Lees *et al.*, 2005), an ecology that is unusual amongst coccolithophores, and both can occur in bloom/(near-)monospecific abundances. The two groups have very close origination dates, in the latest Jurassic (Late Tithonian), within around 0.5Myr of one another (Casellato, 2010, fig.16), although nannoconids became extinct in the Late Campanian, whilst *Braarudosphaera* is extant. **Included families:** Braarudosphaeraceae, Nannoconaceae. **Occurrence:** Upper Jurassic-Recent.

Family **BRAARUDOSPHAERACEAE** Deflandre, 1947

Braarudosphaera wendleriae sp. nov.

Pl.4, figs 8-11. **Derivation of name:** After Dr. Ines Wendler, benthic foraminifera expert on the TDP team. **Diagnosis:** SEM – very small *Braarudosphaera* with elements that are rounded at the tips and in which the tips occur very close to the suture with the adjacent element. In XPL, this species has very low, grey birefringence. **Differentiation:** The small size, roundness of the tips of the elements and relative position of the tips distinguish *B. wendleriae* from all other species of *Braarudosphaera*. **Holotype:** Pl.4, fig.8. **Dimensions:** D = 1.9 μ m. **Paratype:** Pl.4, fig. 10. **Type locality:** TDP Site 31, WNW of main road, SW of Lindi, coastal Tanzania. **Type level:** TDP31/63-1, 13cm, UC6b, Lower Turonian. **Occurrence:** TDP Sites 31, 34, 38; Lower Turonian; UC6b.

Family **NANNOCONACEAE** Deflandre, 1959

Nannoconus funiculus sp. nov.

Pl. 3, figs 1-20. **Derivation of name:** From the Latin '*funiculus*', meaning 'a slender rope', referring to the structure of this species. **Diagnosis:** SEM - elongate, narrow, tapering nannoconid with a relatively narrow central canal, formed from a double-helix-like arrangement of elements that are loosely arranged at the base, giving an ornate appearance to the lower part, and more tightly arranged at the apex, producing a smooth, parallel-sided, rope-like structure. The basal plate/cycle of this species is composed of a single? cycle of more-or-less horizontal-lying, subtriangular elements, the outer edges of which are rounded and which appear to slightly imbricate (Pl.3, figs 19, 20). Above this is a cycle of widely-spaced, radial, elongate,

subrhomboidal? elements that sit on, or are fused with, the basal (subtriangular elements) cycle (Pl.3, figs 13, 20). In the cycles above, it is not clear whether the structure is composed of rhomboidal elements or a combination of these with the type of elements previously described as *Micrantholithus? nicholasii* (Pl.4, figs 2, 3, and see below for a revision of the taxonomy), which are subtriangular, with the outer edge being scalloped, so as to produce a rounded point and two depressions along that edge, giving a trilobed appearance. In Pl.3, fig.17, the elements of a section through an ornate part of the nannoconid are clearly rhomboidal, and this is also more or less so (subrectangular/subrhomboidal) in a section through the smooth, apical part in Pl.3, figs 11 and 16, the difference being the orientation of the elements. However, side-views of the alignment of elements in the ornate part of the nannoconid suggest that they are composed of the scalloped-triangular elements (Pl.3, figs 12-14), and it is thus possible that the ornate-rhomboid part (Pl.3, fig.17) is an apical portion of this nannoconid, transitioning into the rectangle/rhomb-structured, single-rope, apical feature. So, until we have more information, the ornate, helical portion of this nannoconid is produced by either one point of a narrow rhomb or the scalloped edge of a triangular element pointing outwards. These elements are arranged at an angle, stacked in layers of around six per helix, and imbricate. The double-helix effect is produced by the points of the rhombs/scalloped edge of one strand being offset by one point from the other strand, giving the appearance of two ropes spiralling upwards together (Pl.3, fig.15). The apical portion of this nannoconid appears to be composed of subrectangular/subrhomboidal elements, but here they are arranged with a straight edge outwards, so as to produce a smooth, parallel-sided appearance (Pl.3, figs 10, 11, 16). The double-helix effect is less noticeable in this portion because of this, with the two strands being distinguished only by a striped effect in the SEM (Pl.3, fig.11). This apical portion can vary dramatically in length (compare Pl.3, fig.10 with fig.15), and appears to terminate in a knob (Pl.3, fig.15), although most of our specimens are broken. Consequently, it is not possible to give a definitive length for the holotype. In the LM, *N. funiculus* is distinctively highly birefringent, even when rotated, with a relatively very narrow, tapering outline and narrow canal, and with an angled-striped appearance, due to the distinctive double-helix arrangement of the elements. **Differentiation:** The new species is somewhat dissimilar to other nannoconids, being very narrow, elongated and composed of a double-helix-like arrangement of elements of variable shape; however, other species have ‘scalloped’ outer morphologies (e.g. *N. abundans*) and there are enough shared characteristics for *funiculus* to be reasonably included in *Nannoconus*. **Holotype:** Pl.3, fig.15. **Dimensions:** L = 8.0µm (but note that the length of the

apical 'rope' structure is highly variable: Pl.3, fig.10 L = 14.3 μ m), W = 3.0 μ m at widest, 0.6 μ m at narrowest. **Paratypes:** Pl.3, figs 10-14, 19, 20. **Type locality:** TDP Site 31, WNW of main road, SW of Lindi, coastal Tanzania. **Type level:** TDP31/63-1, 13cm, UC6b, Lower Turonian. **Occurrence:** TDP Sites 31, 34, 36; Lower-Upper Turonian; UC6b-UC8.

Nannoconus nicholasii (Lees, 2007) emend. et comb. nov.

Basionym: *Micrantholithus? nicholasii* Lees, 2007, p.50, pl.2, figs 23-27 (27 = holotype). Lees, J.A. 2007. New and rarely reported calcareous nannofossils from the Late Cretaceous of coastal Tanzania: outcrop samples and Tanzania Drilling Project Sites 5, 9 and 15. *Journal of Nannoplankton Research*, **29**(1): 39-65.

Pl. 4, figs 1-7. **Emended description:** Since the original description of this species, based on individual elements seen in the LM (Pl.4, fig.6), we have found these elements in associations in the SEM that allow us to determine that these are nannoconid, not micrantholithid, elements (Pl.4, fig.2). Although our description of *N. funiculus* allows for at least part of its structure to be made of a similar type of element, those Lees (2007) originally described belong to a nannoconid found more commonly in the LM in the original samples of TDP Site 15. This medium-sized species is a relatively short and wide, parallel-sided nannoconid, with a narrow canal. It is composed of subtriangular elements with one scalloped edge, resulting in a point in the middle of that edge, giving the appearance of a trilobed fan. Each element has two sutures, extending from the incised parts of the scalloped edge and meeting at the opposing point. The elements also exhibit striae on their faces (Pl.4, figs 2, 3). These elements are arranged subhorizontally in this nannoconid, with the scalloped edge facing outwards (Pl.4, fig.1). The elements imbricate, with one-third of one element covering one-third of the previous element, such that the lobes of the scalloped edges are always in alignment, giving a vertically ribbed effect in side view and an angular-petaliform end view (Pl.4, figs 4, 5). In the LM, these are most commonly seen in end view, typified by a distinctive outline and relatively low birefringence for a nannoconid.

Differentiation: As far as we know, this is the only nannoconid composed of scalloped-subtriangular elements (apart from potentially *N. funiculus*). The end view of *N. nicholasii* is slightly reminiscent of that of *N. inornatus*, but *N. nicholasii* has a more sculpted outline that is not as crenulated as that of *N. inornatus*. **Paratype:** Pl.4, fig.1. **Dimensions:** L = 5.2 μ m, W = 7.0 μ m. **Occurrence:** TDP Sites 22, 31, 39; Lower Turonian-Coniacian; UC6b-UC10.

4.2.2 Incertae sedis nannoliths

Kokia kayae sp. nov.

Pl. 5, figs 1-8. **Derivation of name:** After Kaya MacLeod, daughter of the TDP Phase II team co-chief and geochemist. **Diagnosis:** SEM – large to very large species of *Kokia* with seven radial, tapering, pointed rays that are free along at least half their length. This nannolith is flat to very slightly concavo-convex, and appears to be composed of numerous, tangentially-arranged laths that thicken and/or become more vertically orientated around the periphery of the nannofossil. The sutures in our SEM specimen are not clearly defined. In the LM, three to four elements go into extinction together on rotation of the nannolith and the sutures between these are radial. There appears to be a depression at the centre of the lith. **Differentiation:** *Kokia* has only previously been reported from the Lower Cretaceous (*e.g.* Kok, 1985; Perch-Nielsen, 1988; van Niel, 1994; Bown *et al.*, 1998) and both species, *borealis* and *curvata*, were defined as only having eight rays each. *Kokia curvata* has very little free-ray length, and so is quite distinct from *K. kayae*, whereas *K. borealis* is defined as having one-quarter to one-half free-ray length, but this might be affected by preservation. The new species differs from *K. borealis* in having seven rays, with greater free-ray length, a distinct extinction pattern and an Upper Cretaceous occurrence. This taxon differs from *Quadrum (Eprolithus?) giganteum* Varol, 1992, which occurs around this level, but which has nine elements/rays and possibly two cycles. *Biantholithus* differs from *Kokia* in having clearly separate radial elements (seen in SEM), not much free-ray length and two shields, when well preserved. **Holotype:** Pl.5, fig.6. **Dimensions:** D = 14.0µm. **Paratype:** Pl.5, fig.8. **Type locality:** TDP Site 36, W of main road, SW of Lindi, coastal Tanzania. **Type level:** TDP36/11-1, 1cm, UC6b, Lower Turonian. **Occurrence:** TDP Sites 22, 26, 31, 34, 36; Lower Turonian; UC6b.

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for supplying the map. We are grateful to Kevin Cooper and Matt Hampton who reviewed this manuscript and raised several interesting points, which we may or may not have agreed with, but which we hope will end up as a discussion thread on *Nannotax3*, as they were insightful and worthy of further discussion.

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Captions

Figure 1: Location of TDP Sites 31 and 36, coastal Tanzania (after Jiménez Berrocoso *et al.*, 2012, 2015). Samples from these sites examined in SEM

Table 1: Ages of all samples referred to herein. Those in bold examined in SEM

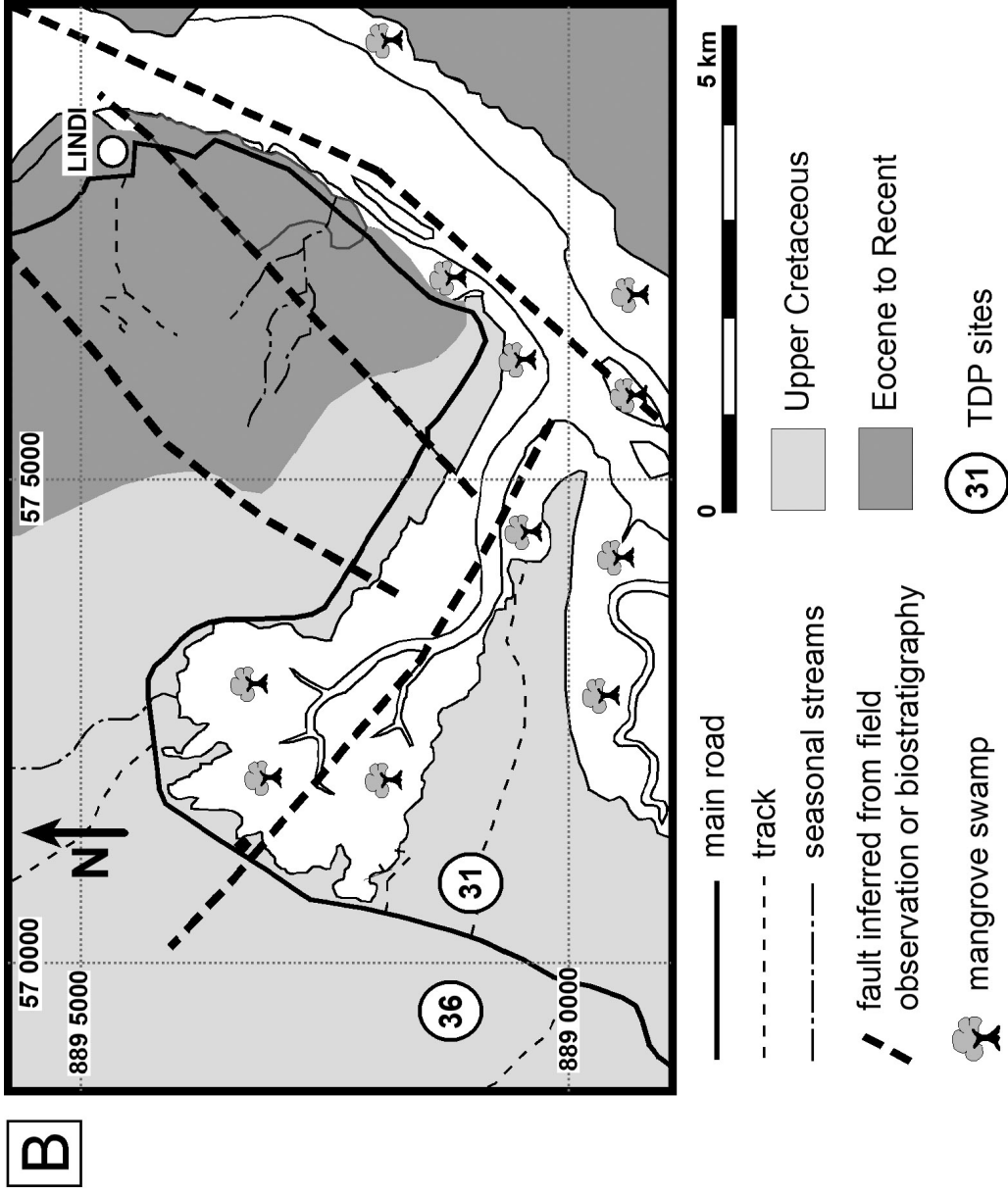
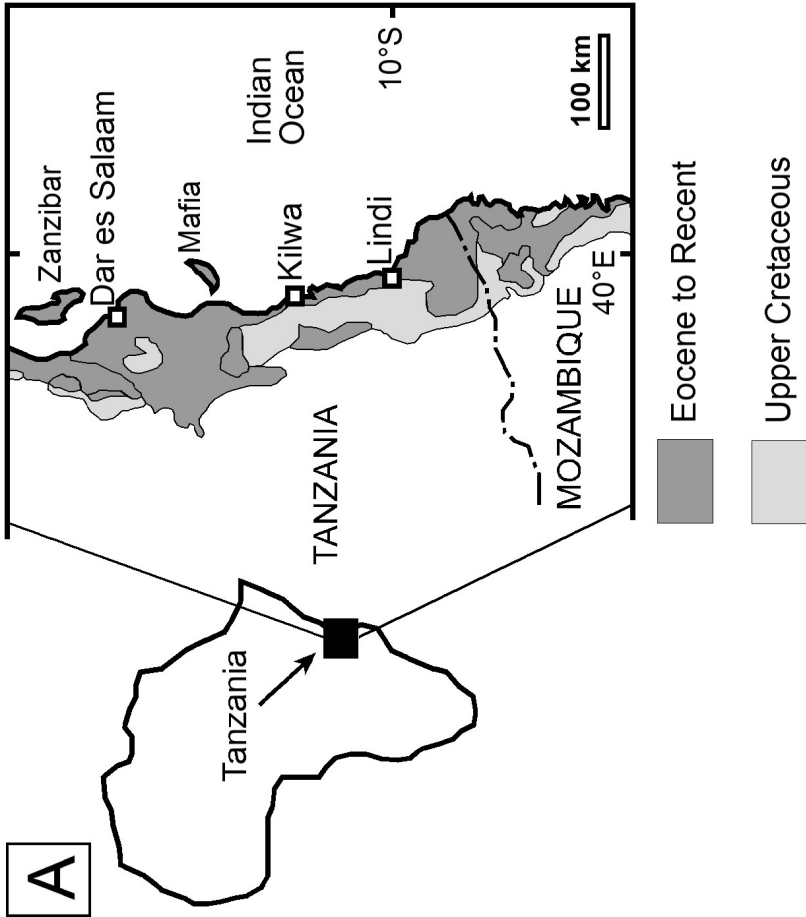


Plate 1

Jimenezberrocosoia birchiae, *J. bosunensis*

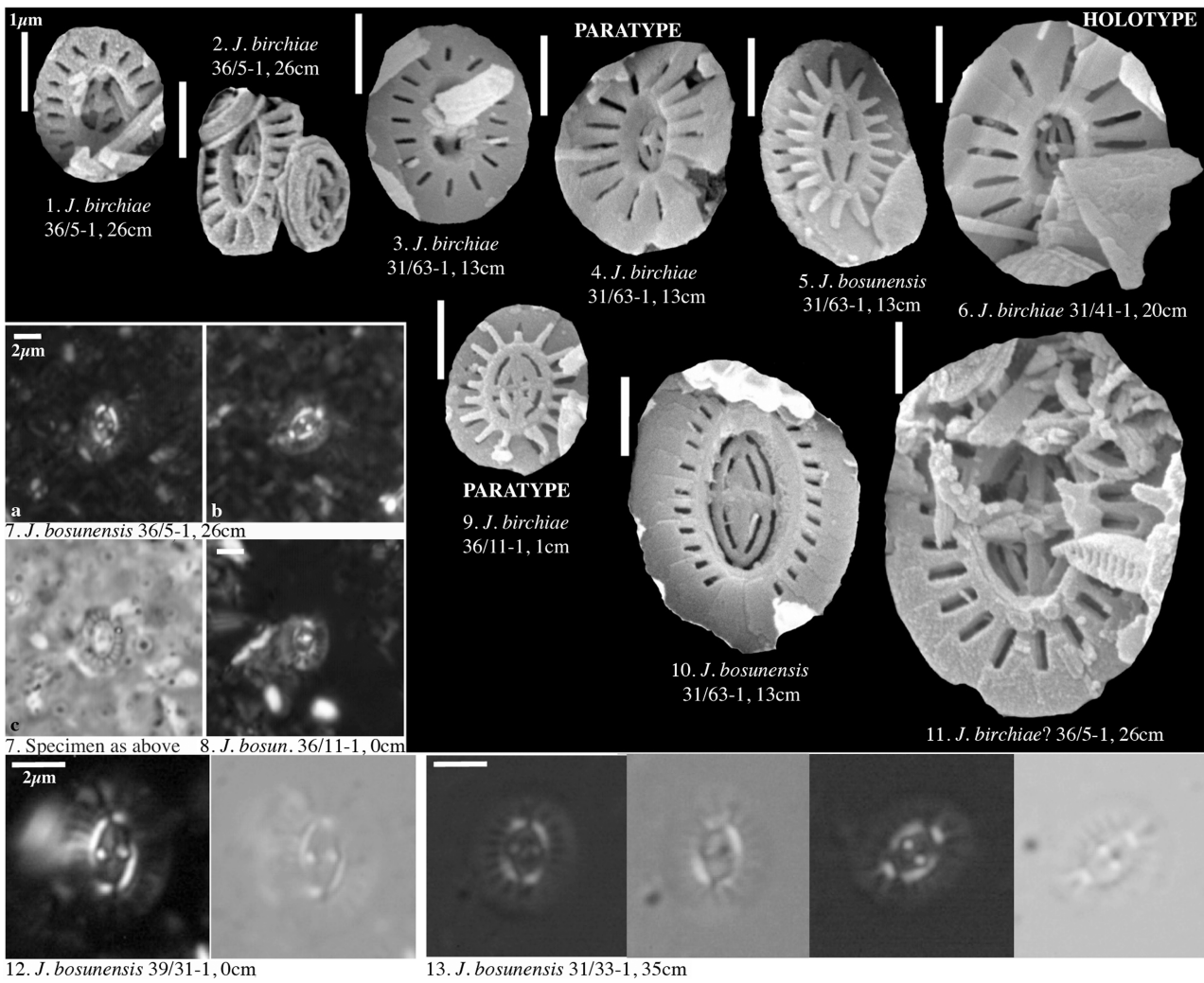


Plate 2

Ellipsolithus linnertii, *E. anadoluensis*, *Petrarhabdus? kirenii*

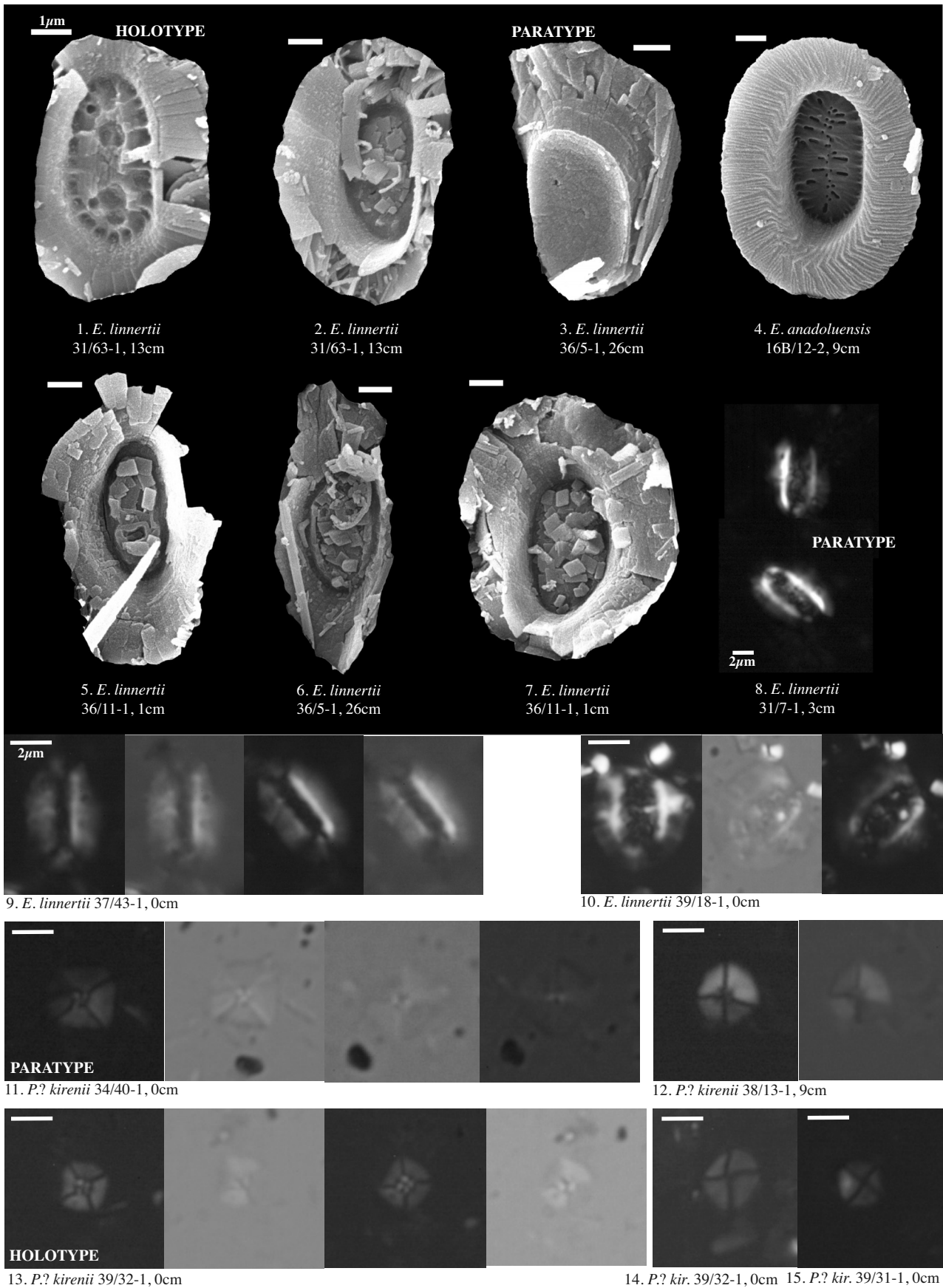
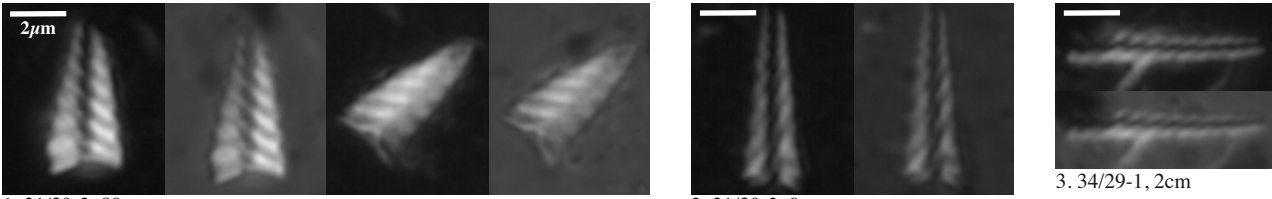


Plate 3

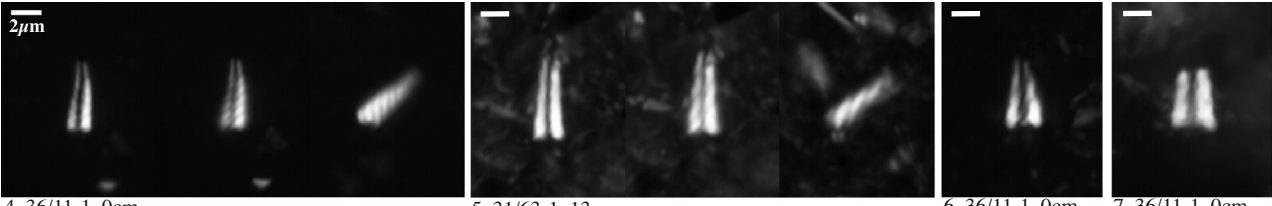
Nannoconus funiculus



1. 31/30-2, 89cm

2. 31/30-2, 0cm

3. 34/29-1, 2cm

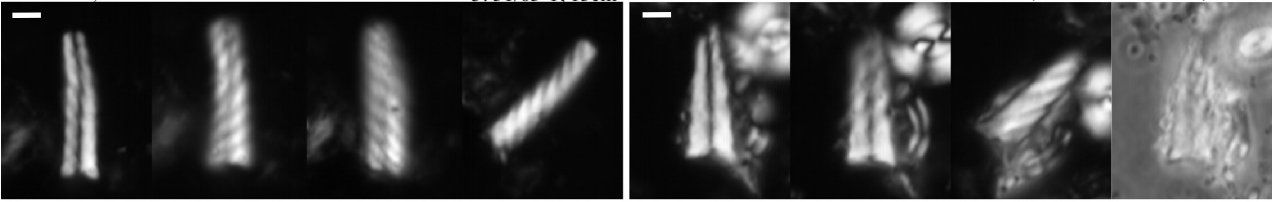


4. 36/11-1, 0cm

5. 31/63-1, 13cm

6. 36/11-1, 0cm

7. 36/11-1, 0cm



8. 36/11-1, 0cm

9. 36/11-1, 0cm

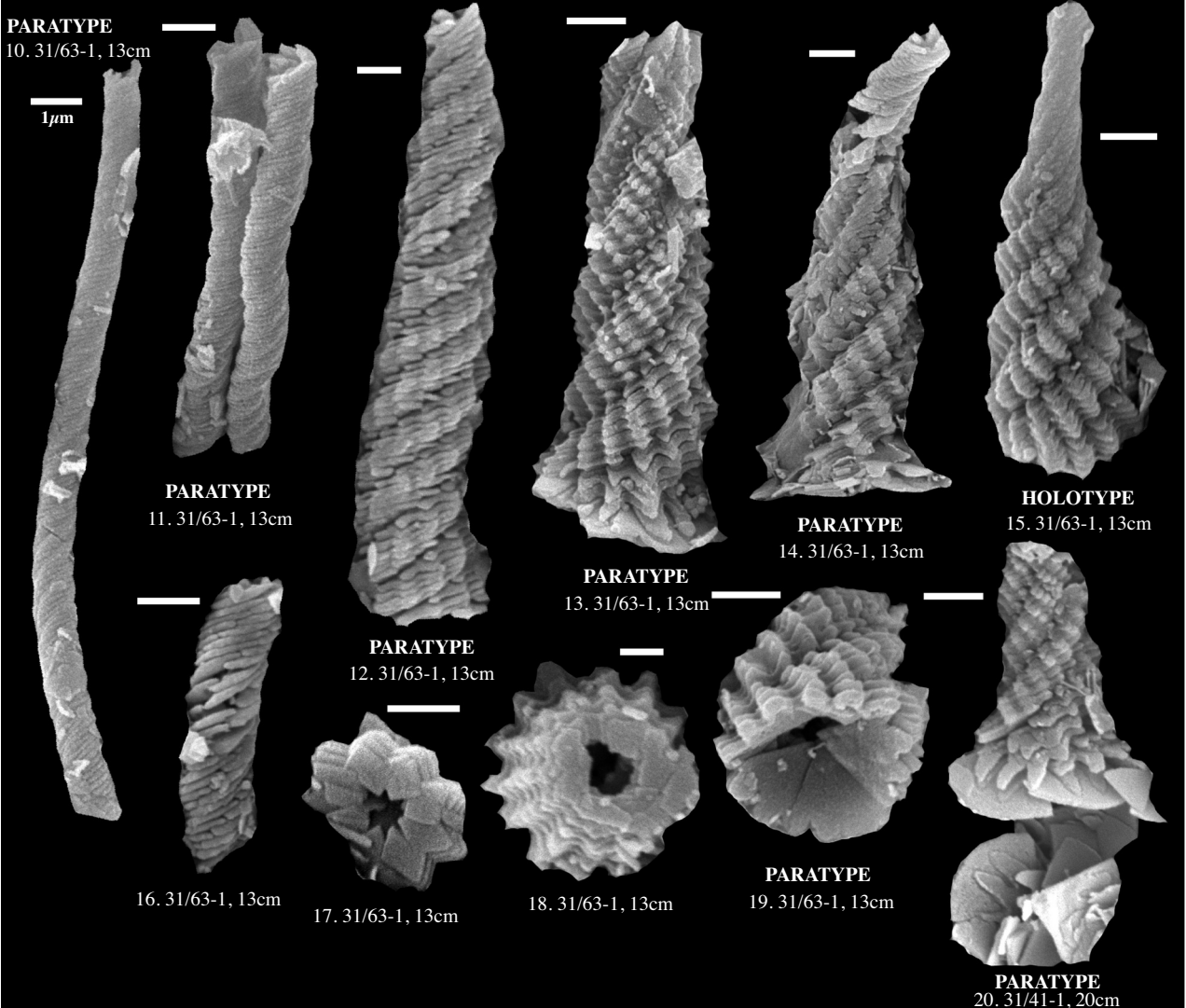


Plate 4

Nannoconus nicholasii, *Braarudosphaera wendleriae*

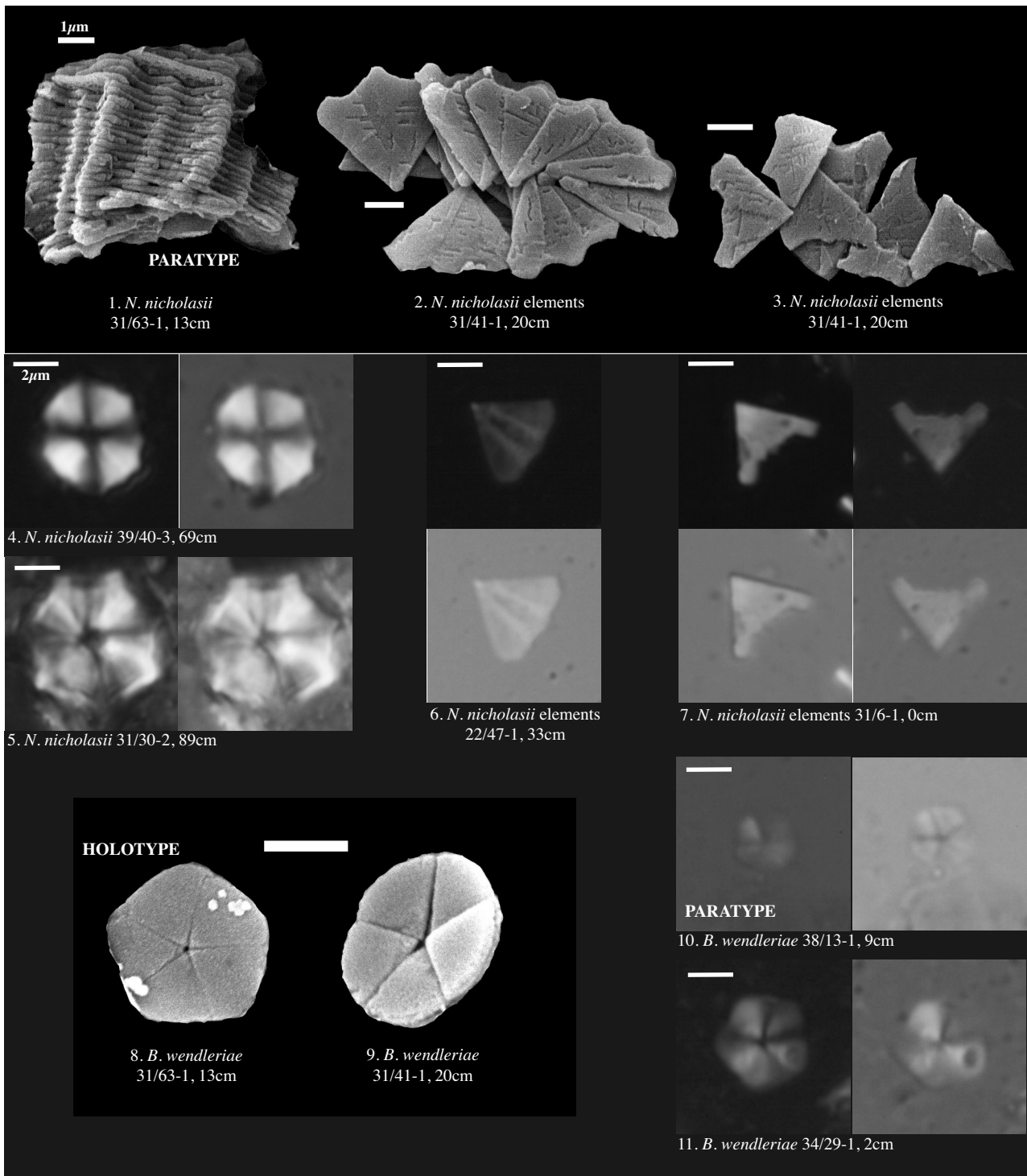
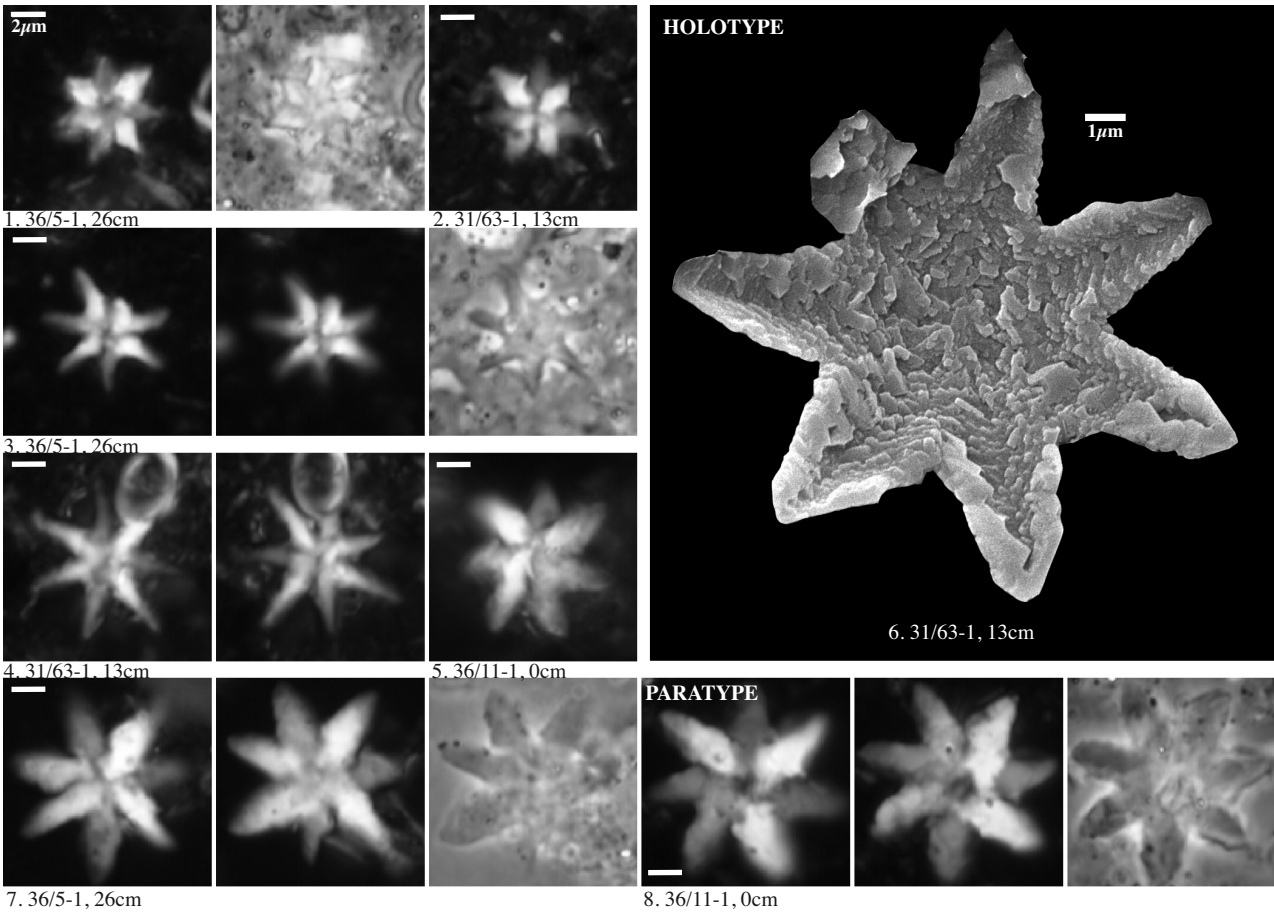


Plate 5
Kokia kayae



SAMPLE	AGE	NANNOFOSSIL ZONE
16B/12-2, 9cm	uppermost Paleocene	NP9a
22/47-1, 33cm	Lower Turonian	UC6a
31/6-1, 0cm	Upper Turonian	UC9b
31/7-1, 3cm	Middle-Upper Turonian	UC9a
31/30-2, 0cm	Lower-Middle Turonian	UC8
31/30-2, 89cm	Lower-Middle Turonian	UC8
31/33-1, 35cm	Lower Turonian	UC6b-UC7
31/41-1, 20cm	Lower Turonian	UC6b-UC7
31/63-1, 13cm	Lower Turonian	UC6b
34/29-1, 2cm	Lower Turonian	UC6b-UC7
34/40-1, 0cm	Lower Turonian	UC6a
36/5-1, 26cm	Lower Turonian	UC6b
36/11-1, 0cm	Lower Turonian	UC6b
36/11-1, 1cm	Lower Turonian	UC6b
37/43-1, 0cm	Lower Maastrichtian	UC20a ^{TP}
38/13-1, 9cm	Lower Turonian	UC6b-UC7
39/18-1, 0cm	Coniacian-Santonian	UC11
39/31-1, 0cm	Coniacian	UC10
39/32-1, 0cm	Coniacian	UC10
39/40-3, 69cm	Coniacian	UC10