J. Nannoplankton Res. **37** (2–3), 2017, pp.145–175 © 2017 International Nannoplankton Association
ISSN 1210-8049 Printed by The Sheridan Press, USA

Oligocene to Pleistocene taxonomy and stratigraphy of the genus *Helicosphaera* and other placolith taxa in the circum North Atlantic Basin

Todd Boesiger*
ALS Global, Lincoln, NE 68506 USA; *tboesig@gmail.com

Eric de Kaenel
DPR, Chemin sous la Roche 4b, 1185 Mont-sur-Rolle, Switzerland; edekaenel@bluewin.ch

Jim Bergen
Paleo at the Hill Country, Brenham, TX 77833 USA; jbnanno@att.net

Emily Browning
BP America, Inc., 200 Westlake Park Blvd, Houston, TX 77079 USA; Emily.Browning@bp.com

Stacie Blair
Blair Biostratigraphy, Cypress, TX 77429 USA; stacie.blair81@gmail.com

Manuscript received 29th September, 2016; revised manuscript accepted 13th June, 2017

Abstract The genus *Helicosphaera* has been widely used for zonal markers in the Oligocene-Pleistocene interval. An overview of *Helicosphaera* is presented to clarify the taxonomy and biostratigraphy of species within the BP framework developed for the deep-water Gulf of Mexico Basin. Age calibrations were obtained from research on ODP Leg 154 core materials in the western equatorial Atlantic. Thirty-eight *Helicosphaera* species are considered herein and are placed into nine morphologic groups. Seven new species are described: *Helicosphaera alata*, *H. bipuncta*, *H. disrupta*, *H. huangii*, *H. lenticulata, H. theodoridisii* and *H. zeta*. A limited number of taxa from eight other placolith genera important to Gulf of Mexico biostratigraphy are also considered and include four new species, *Coronocyclus mesostenos*, *Dictyococcites albitectus*, *Reticulofenestra kahniae* and *Reticulofenestra pospichalii. Dictyococcites gartneri* is introduced as a new combination. Fifty-one main biostratigraphic events are presented for the Gulf of Mexico and ODP Leg 154 from 30.431Ma to 1.246Ma.

Keywords *Helicosphaera*, placoliths, nannofossils, Oligocene, Miocene, Pliocene, taxonomy, Leg 154, Gulf of Mexico, biostratigraphy.

1. Introduction

The merger of BP with Amoco and Arco Vastar around the turn of the century challenged staff to integrate three different and company-specific Cenozoic calcareous microfossil frameworks for the Gulf of Mexico Basin (GoM). The resulting Neogene framework yielded an improved biostratigraphic resolution of 141kyr. Following this, a fourteen-year research program on ODP Leg 154 core materials from the Ceará Rise in the western equatorial Atlantic (Figure 1) provided a cyclostratigraphic-based age model for the Early Oligocene (30.679Ma) through Early Pleistocene (1.595Ma). To our knowledge, this is the only fully astronomically-tuned industrial framework. This internal research program also included work on the Oligocene-Miocene boundary GSSP in Italy (de Kaenel & Bergen, 2008; Bergen *et al*., 2009; de Kaenel & Villa, 2010). Research on the Leg 154 material was conducted at an average sample resolution of 21kyr, roughly akin to that of a precession cycle. The details of our age model with sample depths and ages will be presented in Bergen *et al.* (in prep.) and are based on the astronomically tuned cycles developed by Shackleton & Crowhurst (1997) and Pälike *et al*. (2006) on ODP Leg 154. This age model has been recalibrated to the orbital solution of Laskar *et al*. (2004).

An extensive taxonomic discussion and revision of Neogene species must precede publication of the astronomically-tuned BP Gulf of Mexico Neogene chronostratigraphic chart, currently in preparation for publication as "BP Gulf of Mexico Neogene Astronomically-Tuned Time Scale" (GNATTS; Bergen *et al*., in prep). The series of five manuscripts produced for this volume are focused on the stratigraphically-significant genera *Helicosphaera*, *Sphenolithus* and *Discoaster* (three papers). Other taxa significant to the Gulf of Mexico Neogene are also discussed in these papers and include the genera *Amaurolithus*, *Calcidiscus*, *Camuralithus, Catinaster*, *Ceratolithus*, *Coccolithus, Coronocyclus*, *Cryptococcolithus, Cyclicargolithus*, *Dictyococcites*, *Ilselithina*, *Minylitha* and *Reticulofenestra*.

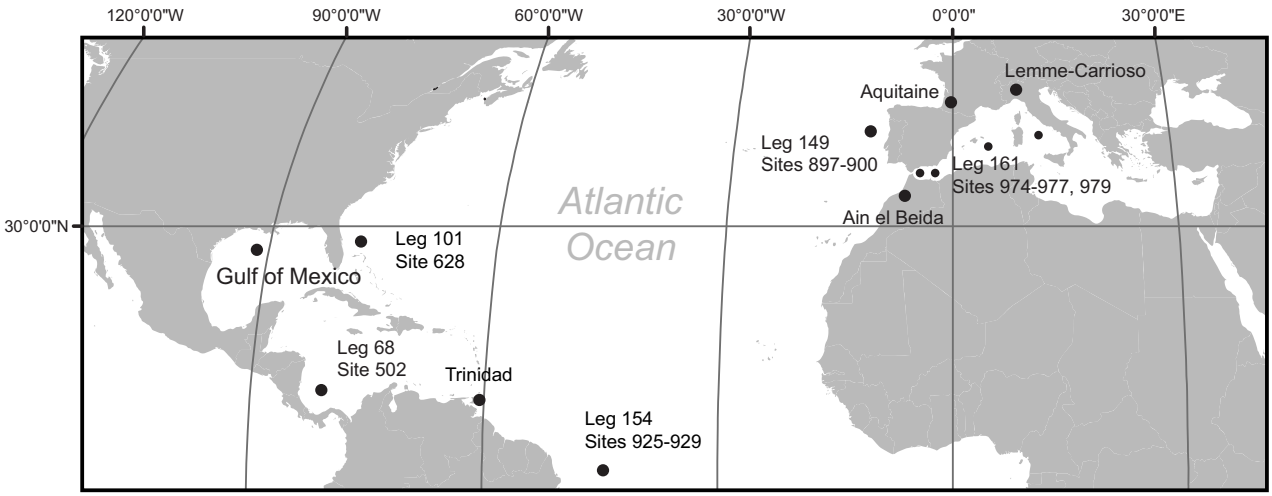


Figure 1: Location map showing the location of deep sea drilling sites and land sections

2. Materials and methods

Lithic materials used for this study are from outcrop, core and well cuttings. ODP Leg 154 collections at the IODP repository in Bremen (Germany) provided the main source for core material; ODP sample request numbers: 18687A (2003), 18687B (2005), 20484A (2005), 20484B (2006), 22364B (2011), 22433A (2011). Other collections used were from: (1) DSDP Leg 68 (Site 502) in the western Caribbean Sea; (2) ODP Leg 149 (Holes 897C, 898A, 899A, 899B and 900A) in the northeast Atlantic Ocean; (3) ODP Leg 161 (Holes 974B, 975B, 976B, 977A and 979A) in the western Mediterranean; (4) the Ain el Beida section (Atlantic margin of Morocco); (5) ODP Leg 101 (Site 628A) in the western North Atlantic Ocean; (6) the base Neogene GSSP section near Lemme-Carrioso, section in northern Italy; (7) the historical Stratotype of the Aquitanian (Aquitaine, Southwest France), and (8) the Trinidad "Bolli collection" sampled by H.M. Bolli in 1957 (Bolli, 1957). Many important Late Paleogene and Neogene (Miocene) taxa have been published from the Bolli collections (Bramlette & Wilcoxon, 1967; Bukry & Percival, 1971; Gartner, 1967; Hay *et al*., 1967; Martini & Bramlette, 1963; Roth, 1970; Roth *et al*., 1971), but none in the past 45 years. Deep-water Gulf of Mexico well materials are predominantly ditch-cutting samples.

The low-latitude composite section from Leg 154 was sampled at a minimum of 18kyr resolution from the intra lower Oligocene (30.679Ma) to the lower Pleistocene (1.595Ma); 1626 samples from this deep-sea section were sampled and 1366 samples examined in detail as part of the current study. We placed the Pliocene/Pleistocene boundary at the top of the Gelasian Stage at 1.806Ma following the astronomical tuned age of Lourens *et al*. (1996), although we do recognize the base of the Pleistocene was moved to the base of the Gelasian Stage in 2009 by the Executive Committee of the International Union of Geological Sciences (IUGS). This transfer of the Gelasian Stage is not followed in this study because the BP GNATTS (Bergen *et al.*, in prep) has not yet adopted the new Pliocene/Pleistocene boundary placement at the top of the Gelasian Stage. This omission is necessary to avoid confusion and maintain consistency with the GoM industry standard that continues to place the boundary at top of the Gelasian Stage on the last occurrence of *Discoaster brouweri*. The following stratigraphic abbreviations are used: LO (lowest occurrence) and HO (highest occurrence). Abundance modifiers are: R (regular), or a persistent presence in adjacent samples for LRO and HRO; F (few), for specimens observed, roughly, every 10 fields of view for LFO and HFO; C (common), for specimens observed in each field of view for LCO and HCO.

The objective of this work is to clarify taxonomic concepts and present the GoM stratigraphy developed over the past five decades from the three BP heritage companies (Amoco, Arco Vastar, and BP), not to compare our results to other published stratigraphies of the GoM Basin or research on ODP Leg 154. The geologic ages derived from sampling of ODP Leg 154 are maintained at three decimal precision throughout the manuscript for consistency; error stated for ages are the difference in age for the next sample analyzed upwards or downwards in the composite section. Link to supplementary materials are provided and include biometrics (http://ina.tmsoc.org/JNR/JNRcontents.htm).

3. Biostratigraphy

The primary zonation (NP/NN Zones) referred to herein is Martini (1971), although the zonation (CP/CN Zones) of Okada & Bukry (1980) is also referred to within the text. Any new zones or emendations are presented by de Kaenel *et al*. (2017) and Blair *et al*. (2017) in this volume; these include introduction of Zone NP26 at the top of the Oligocene and subdivision of Zone NN12. The BP Gulf of Mexico Neogene Astronomically Tuned Time Scale (GNATTS) is currently in preparation for publication and contains the details of the BP Gulf of Mexico

age model, biostratigraphic horizon nomenclature, and event stratigraphy and calibration (Bergen *et al*., in prep). The GNATTS is calibrated to the Astronomically-Tuned Neogene Time Scale 2004 (ATNTS2004) of Lourens *et al*. (2004) and correlated to the standard zonation schemes of Martini (1971) and Okada & Bukry (1980), with some emendations.

All stratigraphic ranges of the species are expressed in NP/NN Zones with the assignment ages obtained by our study of Leg 154 materials. It is important to note that the ATNTS2004 and ATNTS2012 (Gradstein *et al*., 2012) are astronomically-tuned from the same materials we used for the composite depth section of Leg 154. By sampling the same section, direct age estimations were obtained for the calcareous nannofossil and foraminifera events. Important biostratigraphic events utilized in the GoM are presented in Table 1, which include some standard events used on a global scale. The stratigraphic ranges and ages for all *Helicosphaera* species are presented in Figures 2 and 3, along with drawings of each species.

4. Systematic Paleontology

Helicosphaera is the focus of this manuscript and presented first. The remaining genera are not considered in detail and include: *Calcidiscus*, *Camuralithus*, *Coccolithus*, *Coronocyclus*, *Cryptococcolithus*, *Cyclicargolithus* and *Reticulofenestra*. For these seven genera, only species relevant to the BP GNATTS are presented; the genera are organized on the final two plates by birefringence and follow *Helicosphaera* in the text by order of appearance on the plates.

The calcareous nannofossil terminology used herein follows Young *et al.* (1997) to define characteristics as observed in light microscope (Figure 4). From this, we stress the terms applied to coccolith size: very small (<3μm); small (3 to <5μm), medium (5 to <8μm); large (8 to <12μm); and very large (>12μm). Terms used to classify the coccolith shape follow Bown & Dunkley Jones (2012), who emended the subdivisions presented by Young *et al.* (1997). Only taxonomic references not present in Perch-Nielsen (1985) are included in the reference list. The aspect ratios (AR) used to categorize coccolith shape are: circular (1.00–1.03), subcircular (1.04–1.09), broadly elliptical (1.10–1.25), normally elliptical (1.26–1.45), and narrowly elliptical (>1.46). The size of the central area (CA) is also defined by the ratio of the width of the central area divided by the width of the placolith and multiplied by 100. Three central area (CA) categories, expressed as percentages, are: small (CA<25%), medium (CA 25–50%) and large (CA>50%).

Genus *Helicosphaera* Kamptner, 1954

It has been nearly twenty years since a comprehensive taxonomic review of the genus *Helicosphaera* was published; most notable are by Theodoridis (1984), Perch-Nielsen, (1985), Aubry (1990), and Young (1998). Our intent is to summarize and organize species relevant to the BP Neogene GoM biostratigraphic framework. This extends back into the Middle Oligocene (30.679Ma) because of our research program, but also includes related species necessary to taxonomic distinction. It is not comprehensive for this span of geologic time, nor are all described and extant species considered. We do recognize that a comprehensive treatment of this genus is needed, but our purpose is to focus on the taxonomic and biostratigraphies used within the three heritage companies and BP GoM since the turn of the century.

Thirty-eight *Helicosphaera* species are considered herein and presented in Table 2. The details of our groupings are founded on Theodoridis (1984) with some minor differences. The nine groups presented in Table 2 are subdivided on four basic morphologic properties. Interference type is primary and corresponds to the three groups as defined by Theodoridis (1984; p. 96, fig. 54) based on the type of birefringent blanket:

Type I. Blanket confined to the central area.

Type II. Blanket covering the central area on one side and the distal surface on the other side.

Type III. Blanket covering the entire distal surface.

The remaining three properties used to differentiate groups are: (1) peripheral outline; (2) flange or termination shape; and (3) bar type. Species are introduced in both the text and plates relative to the nine groupings shown in Table 2, where each group is referred to by a representative species. Further morphologic distinction is made within three of the 38 species, where there is proven stratigraphic utility in the GoM and/or our Leg 154 research (*H. ampliaperta*, *H. sellii* and *H. euphratis*).

4.1 *Helicosphaera carteri* group

We have included only six taxa relevant to the GoM; they range from the Lower Oligocene to the Pliocene, with the exception of the extant *H. carteri*. The group is categorized by a conjunct bar and a type III interference pattern. Species are distinguished by geological age and central structures (Table 2).

***Helicosphaera carteri* (Wallich, 1877) Kamptner, 1954**

Pl. 1, figs 1–4

1877 *Coccosphaera carteri* Wallich, p. 348, figs. 3, 4, 6, 7, 7a, 17

1954 *Helicosphaera carteri* (Wallich, 1877) Kamptner, p. 21, text-figs. 17–19

Remarks: *Helicosphaera carteri* is medium to very large (5–14μm) with a rounded flange (termination) and two longitudinal pores. In some specimens, the rounded flange is extended and forms a wing (Pl. 1, figs 3–4). Similar Neogene forms, such as *H. paleocarteri*, with variations of the central area (e.g. pore position, slits or completely closed) were often grouped with *H. carteri* during analyses. *Helicosphaera ethologa* is morphologically similar,

Taxon	Event	Zone Martini, 1971	Age (Ma)	Error$_1$ (Ma)	Hole-Core-Sec. cm-cm	Depth (rmcd)$_2$
H. sellii	HO	NN19c	1.246	–	ODP Leg 161, Site 979	–
H. sellii (open)	HO/HRO	NN19c	1.276	–	ODP Leg 161, Site 977	–
H. sellii	INC/HCO	NN19c	1.357	–	ODP Leg 161, Site 975B	–
C. macintyrei	HO	**NN19b**	1.607	0.012	926C-5H-6, 24–25	50.62
C. macintyrei	INC	NN19b	1.634	0.007	926B-6H-1, 89–90	51.84
H. zeta	HO	NN15	4.069	0.007	926B-13H-1, 119–120	126.94
H. intermedia	HO	NN15	4.102	0.017	926B-13H-2, 78–79	128.03
C. mediaperforatus	HO	NN14	4.644*	0.020	926B-14H-5, 120–121	144.11
C. mediaperforatus	HO	NN12	5.258$^+$	0.014	926A-16H-4, 49–50	159.95
C. pelagicus	HCO	NN11b	6.550	0.017	926B-18H-5, 121–122	186.25
H. orientalis	HO	NN11a	7.667	0.021	926B-20H-2, 142–143	203.61
H. orientalis	HRO	NN11a	7.848	0.023	926B-20H-5, 10–11	206.79
C. pliopelagicus (>11)	HO	NN9	10.800	0.025	926A-25H-3, 147–149	252.83
H. bownii	HO	NN9	10.850	0.017	926A-25H-4, 56–58	253.42
C. miopelagicus (>14)	HO	NN8	10.996	0.012	926A-25H-5, 80–82	255.16
C. premacintyrei	HO	NN6	12.368	0.025	926A-27H-4, 13.5–15.5	274.86
H. rhomba	HO	NN6	12.821	0.031	926A-28H-1, 86–88	281.06
H. rhomba	HRO	NN6	12.930	0.039	926A-28H-2, 127–129	282.97
C. bukryi	HO	NN6	12.989	0.021	926A-28H-3, 99.5–101.5	284.20
R. kahniae (<8)	HO	NN6	13.067	0.019	926A-28H-4, 107.5–109.5	285.78
H. californiana	HO	NN5	13.495	0.009	926A-29H-4, 10–12	294.30
C. bukryi	HRO	NN5	13.706	0.012	926A-29H-6, 94–96	298.14
R. pospichalii	HO	NN5	13.885	0.008	926A-30H-1, 104–106	301.15
H. californiana	HRO	NN5	13.988	0.015	926A-30H-2, 141–143	303.02
H. scissura	HO	NN5	14.022	0.008	926A-30H-3, 60–62	303.71
C. bukryi	INC	NN5	14.042	0.006	926A-30H-3, 102–104	304.13
H. perch-nielseniae	HRO	NN5	14.280	0.005	926A-30H-6, 139–141	309.00
C. bukryi	top ACME	NN5	14.378	0.019	925A-4H-5, 8–10	358.13
C. bukryi	bot ACME	NN5	14.539	0.017	925C-35H-2, 115–117	365.84
H. ampliaperta	HO	**top NN4**	14.897	0.021	925D-35H-3, 95–96	367.64
R. kahniae (>8)	HO	NN4	14.897$^+$	–	925D-35H-3, 95–96	367.64
D. albitectus	HO	NN4	15.657	0.020	925D-37H-2, 85–87	395.25
D. onustus	HO	NN4	16.018	0.020	925C-38-5, 55–56	408.49
H. ampliaperta (>12)	HO	NN4	16.802	0.025	928A-26X-2, 50–51	258.16
C. premacintyrei	LO	NN4	17.058	0.020	928B-27X-2, 115–117	265.59
H. mediterranea	HO	NN4	17.425	0.018	928B-28X-1, 110–111	273.74
H. ampliaperta (>12)	LO	NN3	18.768	0.024	926B-38X-1, 70–72	376.31
H. ampliaperta	LO	NN3	19.115	0.018	926B-39X-1, 5–6	385.37
H. euphratis s.s.	HO	NN2	19.552	0.021	926B-40X-3, 105–107	398.97
H. recta	HO	NN2	20.170	0.020	926C-41X-5, 120–121	413.07
C. pelliculathus	HO	NN2	20.998*	0.008	926B-44X-4, 95–96	438.66
H. truncata	HO	NN2	21.041	0.029	926B-44X-5, 90–91	440.11
H. disrupta	HO	NN2	21.161	0.019	926B-45X-1, 65–67	443.56
C. pelliculathus	HO	NN2	21.362$^+$	0.020	926B-45X-5, 80–81	449.71
H. bramlettei	HO	NP25	24.870	0.034	926B-55X-4, 90–91	544.72
H. wilcoxonii	HO	NP25	25.061	0.014	925A-26X-4, 125–126	568.60
H. carteri	LO	NP24	26.154	0.027	926B-59X-1, 25–26	578.27
H. compacta	HO	NP24	27.376	0.042	928B-47X-4, 145–146	460.99
H. ethologa	HO	NP24	28.453 *	0.044	925A-36R-6, 15–16	667.89
H. ethologa	HO/HRO	NP23	29.762	0.028	925A-41R-1, 16–17	708.90
D. gartneri	HO	NP23	30.431	0.040	925A-43R-4, 40–41	726.34

Table 1: Main events in the Gulf of Mexico calibrated to ODP Leg 154. Ages (Ma), Zones and positions (revised measured composite depth) of the Oligocene-Pleistocene calcareous nannofosssils

$_1$error is age of next sample; $_2$revised meters composite depth; $^+$GoM event indirect through wells and dated marker; * Leg 154 event is younger than GoM; HO/HRO: HO in GoM coeval to HRO in ODP Leg 154

but restricted to the Lower Oligocene (Plate 1). A stratigraphic gap of 2.3Ma was established between these two species in the Leg 154 research.

Occurrence: *H. carteri* ranges from the Upper Oligocene to Recent in the GoM and Leg 154. Its LO in uppermost Zone NP24 was dated at 26.154Ma in the Leg 154 research (Table 1).

Helicosphaera sellii (Bukry & Bramlette, 1969) Jafar & Martini, 1975

Pl. 1, figs 5–12

1969 *Helicopontosphaera sellii* Bukry & Bramlette, p. 134, pl. 2, figs. 3–7

1975 *Helicosphaera sellii* (Bukry & Bramlette, 1969) Jafar & Martini, p. 391

Remarks: A medium to large, elliptical form with a curved flange and conjunct bar that is at a low angle and normally inclined. The bar separates two medium to large openings, which have rounded extremities and are angular at their juncture with the bar. In the expanded sections of the GoM, two variants with different hole sizes were recognized as successive extinction events by BP. *Helicosphaera* cf. *sellii* was attributed to specimens with smaller holes (~ 1/5 total width) and *H. sellii* to those with larger holes (~ 1/3 of total width) (Pl. 1, figs 11–12). The holotype of *H. sellii* is actually morphologically similar to *H.* cf. *sellii* of BP (Pl. 1, figs 5–10), which has a younger extinction event. The other two original specimens illustrated by Bukry & Bramlette (1969) have larger central openings comparable to the BP GoM concept of *H. sellii*.

Occurrence: Both morphotypes of *H. sellii* range from the Lower Pliocene to Lower Pleistocene. In Leg 154, the LO of *H. sellii* in Zone NN12 is dated at 5.258Ma (926A-16H-4 49–50cm), followed shortly by the appearance (Zone NN13) of the forms with larger central openings, *H. sellii* (open) at 4.978Ma (926B-15H-5 2–3cm). Their extinctions occur in reverse order, where both are long standing BP GoM markers (Table 1). The first downhole increase in *H. sellii* is immediately below these two successive events in the GoM and dated at 1.357Ma (Table 1).

Helicosphaera bownii da Gama & Varol, 2013

Pl. 1, figs 13–18

2013 *Helicosphaera bownii* da Gama & Varol, p. 7, pl. 1, figs. 9–10; pl. 4, figs. 5–6

Remarks: *Helicosphaera bownii* is an elliptical form with a curved flange (termination), a conjunct bar and two medium-sized holes that are angular at their juncture with the bar (Table 1). *Helicosphaera bownii* is distinguished from other species mainly by its middle Miocene extinction, in addition to the bar inclination and the hole size (medium). Arco referred to this species as *H.* cf. *sellii,* not to be confused with the aforementioned BP form of *H.* cf. *sellii*, which is restricted to the Pliocene to Lower Pleistocene.

Occurrence: *Helicosphaera bownii* ranges from the Middle Miocene to Upper Miocene. The HO is a reliable GoM marker observed in lower Zone NN9 and dated at 10.850Ma in the Leg 154 research (Table 1). The LO has been placed in uppermost Zone NN4 in the Leg 154 research and dated at 15.018Ma (Sample 925D-35H-5, 35–37cm; error 0.019Ma).

Helicosphaera mediterranea Müller, 1981

Pl. 1, figs 19–20, 29–30

1981 *Helicosphaera mediterranea* Müller, p. 428, pl. 1, figs. 13–14

1981 *Helicosphaera crouchii* Bukry p. 462, pl. 4, figs. 13–16; pl. 5, figs 1–4

Remarks: The holotype of *H. mediterranea* is 13.0μm with a curved flange (termination), a conjunct bar and two medium to large holes. The conjunct bar is narrow and at a low angle to the minor ellipse axis. *Helicosphaera bownii* is morphologically similar to *H. mediterranea*, but restricted to the Middle to Upper Miocene. A stratigraphic gap of 2.4Ma was established between these two species in the Leg 154 research.

Occurrence: The HO of *H. mediterranea*, a long-standing marker in the BP Gulf of Mexico scheme, is dated in Leg 154 at 17.425Ma (Table 1). It ranges down into the Upper Oligocene (NP24).

Helicosphaera ethologa Bown, 2005

Pl. 1, figs 21–24

1996 *Helicosphaera* aff. *H. carteri* (Wallich, 1877) Kamptner 1954, de Kaenel & Villa, p. 125, pl. 8, figs. 21–24 ; pl. 10, figs. 14–15

2005 *Helicosphaera ethologa* Bown, p. 31, pl. 13, figs. 16–22

Remarks: *Helicosphaera ethologa* is a large, elliptical form with a curved flange and a closed central area with two slightly oblique slits. *H. ethologa* is only distinguished from *H. carteri* by its central area (Table 2). The stratigraphic ranges of these two species do not overlap.

Occurrence: *Helicosphaera ethologa* is restricted to the Lower Oligocene Zone NP23 in the GoM. In Leg 154, the HO of *H. ethologa* is dated at 28.453Ma and the HRO at 29.762Ma (Table 1). The HO of the species is older in the GoM, believed to be equivalent to the HRO in the Leg 154 research. The LO of *H. ethologa* in the deep-water GoM is near the base of Zone NP23, immediately above the HO of *Reticulofenestra umbilica* (top Zone NP22).

Helicosphaera huangii de Kaenel & Bergen, *sp. nov.*

Pl. 1, figs 25–28

Derivation of name: named in honor of nannofossil biostratigrapher T.C. Huang (retired ExxonMobil, Houston, TX) for his contributions to GoM biostratigraphy.

Diagnosis: An elliptical, Early Oligocene *Helicosphaera* species with a type III interference pattern, truncate flange, and a low-angle, conjunct bar separating two medium-sized holes.

Remarks: *Helicosphaera huangii* differs from other species in this group with central holes *(H. mediterranea*, *H. bownii* and *H. sellii*) by its truncated flange and older geologic age. It is referred to as *Helicosphaera* aff. *mediterranea* in BP GoM lexicon.

Holotype dimensions: L = 11.0μm; W = 7.4μm; Aspect Ratio 1.2

Holotype: Pl. 1, figs 25–26

Type locality: South Trinidad, from Bolli (1957)

Type level: Sample JS 19, *Globigerina ampliapertura* Zone, Zone NP23, Lower Oligocene

Occurrence: The Lower Oligocene HO of *H. huangii* in Zone NP23 has been associated with the HO of *Lanternithus minutus* in four deep-water GoM wells, which is below the reach of our Leg 154 research. The specimens illustrated herein were recovered from Trinidad outcrop material dated within Zone NP23.

4.2 *Helicosphaera intermedia* group

Six species are included in this group. The primary diagnostic characteristics are a disjunct bar and type III interference patterns (Table 2). Five species have curved flange-terminations and one species a truncated flange. Bar angle, shape and thickness are variable.

Helicosphaera intermedia Martini, 1965

Pl. 2, figs 1–10

1965 *Helicosphaera intermedia* Martini, p. 404, pl. 35, figs. 1–2

Remarks: The holotype of *H. intermedia* is 10.0μm; its thin, disjunct bar is straight and inclined at a high angle to the minor axis. *Helicosphaera intermedia* is distinguished from other members of this group by its bar morphology. Published specimens with inclined, sigmoidal bars are assigned to *Helicosphaera zeta* sp. nov.

Occurrence: The HO of *H. intermedia* is a marker horizon in the GoM, which has been placed in Zone NN15 and dated at 4.102Ma (Table 1). It ranges down into the Upper Eocene (NP19).

Helicosphaera zeta de Kaenel & Bergen, *sp. nov.*

Pl. 2, figs 11–17

Derivation of name: From the Greek letter *Z*.

Diagnosis: An elliptical *Helicosphaera* species with a type III interference pattern, curved flange and a disjunct bar that is inclined and sigmoid.

Description: An elliptical *Helicosphaera* species with a type III interference pattern. The central bar is disjunct and has a sigmoid outline. The bar is broad and inclined at roughly 45 degrees to the minor ellipse axis. The curved flange (termination) may merge into the side of the helicolith or form a wing. Length = 7–14μm.

Remarks: *Helicosphaera zeta* is distinguished from *H. intermedia* and *H. rhomba* by its sigmoid bar. *Helicosphaera zeta* and *H. leesiae* differ by the inclination and shape of the bar.

Holotype dimensions: L = 7.6μm; W = 5.0μm

Holotype: Pl. 2, figs 11–12

Type locality: ODP Leg 154, Hole 926A, Ceará Rise, western equatorial Atlantic

Type level: Sample 926A-26-4, 11–13cm, Zone NN7, Serravallian

Occurrence: The HO of *H. zeta* is a GoM marker, which has been placed in Zone NN15 and dated at 4.069Ma (Table 1). It ranges down into the Lower Oligocene (NP23).

Helicosphaera leesiae da Gama & Varol, 2013

Pl. 2, figs 21–23

2013 *Helicosphaera leesiae* da Gama & Varol, p. 7, pl. 1, figs. 13–15

Remarks: *Helicosphaera leesiae* is large to very large and its disjunct bar slightly inclined to the minor axis (<10 degrees). The holotype of *H. leesiae* is 12.0μm with a slightly sigmoid bar. *Helicosphaera leesiae* is distinguished from *H. zeta* by the shape and orientation of the bar.

Occurrence: Da Gama & Varol (2013) reported the range of the species from the Upper Oligocene (NP24) to Lower Miocene (NN2).

Helicosphaera rhomba (Bukry, 1971) Jafar & Martini, 1975

Pl. 2, figs 18–20

1971 *Helicopontosphaera rhomba* Bukry, p. 320, pl. 5, figs. 6–9

1975 *Helicosphaera rhomba* (Bukry, 1971) Jafar & Martini, p. 391

Remarks: The holotype is 15.5μm and has a disjunct bar oriented at a high angle to the minor axis. The bar is elongate and rectangular. *Helicosphaera intermedia* and *H. euphratis* also have straight bars oriented at high angles to the minor axis. *Helicosphaera euphratis* has a thick bar which completely fills the central area, whereas *H. intermedia* has a narrower bar than *H. rhomba*.

Occurrence: The HRO of *H. rhomba* is a marker in the GoM and is dated at 12.930Ma (Table 1). The HO of the species, also in Zone NN6, is dated at 12.821Ma (Table 1). In Leg 154, the LO was recorded in Zone NP25.

Helicosphaera euphratis Haq, 1966

Pl. 2, figs 24–29

1966 *Helicosphaera euphratis* Haq, p. 33, pl. 2, figs. 1, 3

1967 *Helicosphaera parallela* Bramlette & Wilcoxon, p. 106, pl. 5, figs. 9–10

Remarks: *Helicosphaera euphratis* is a large to very large species characterized by its rectangular, disjunct bar, which is nearly aligned with the major axis and entirely fills the central area. *Helicosphaera rhomba* has a narrower rectangular bar that does not fill the central area. There is an intermediate form which has a narrower bar similar to *H. rhomba*, but it closes the central area. This form in referred to as *Helicosphaera* aff. *H. euphratis* and its extinction falls between those of the two species.

Occurrence: The HO of *H. euphratis* is a GoM marker within upper Zone NN2 and dated at 19.552Ma in Leg 154 materials (Table 1). In Leg 154, the HO of *H.* aff. *H. euphratis* falls within Zone NN4 and dated at 16.456Ma (925A-9-5, 10–12cm; error 0.019Ma) (Figure 3).

***Helicosphaera truempyi* Biolzi & Perch-Nielsen, 1982**

Pl. 3, figs 1–3

1982 *Helicosphaera truempyi*, Biolzi & Perch-Nielsen, p. 171, pl. 1, figs. 1–8

Remarks: The holotype is 23.3μm with a large, curved flange and large central opening. The long, disjunct bar is aligned with the minor axis and flares at both junctures with the rim. A medial suture line divides the length of the bar. *Helicosphaera truempyi* is distinguished by its very large size (>15μm) and bar morphology.

Occurrence: A range has not been established for this species in the GoM. In Leg 154, the LO within Zone NP25 is dated at 25.714Ma (926B-57X-5 120–121cm; error 0.031Ma) and the HO in Zone NN2 is dated at 21.641Ma (Sample 926B-46X-4 140–142cm, error 0.018Ma).

4.3 *Helicosphaera bramlettei* group

This group includes taxa with disjunct bars and a type II interference patterns (Table 2). The three species included herein have elongate to subrectangular outlines, low angle bars, and variations on a truncate flange. All three have Oligocene extinctions.

***Helicosphaera bramlettei* (Müller, 1970) Jafar & Martini, 1975**

Pl. 3, figs 4–7

1970 *Helicopontosphaera bramlettei* Müller (*pro parte*), p. 114, pl. 5, figs. 5–6; *non* pl. 5, fig. 4

1975 *Helicosphaera bramlettei* (Müller, 1971) Jafar & Martini, p. 390

Remarks: The holotype is 11.0μm and is described from Zone NP25. *Helicosphaera bramlettei* is a medium to large, elongate species. The flange (termination) is pointed and the bar is slightly inclined to the minor axis. *Helicosphaera wilcoxonii* has a truncated flange and its bar is less inclined.

Occurrence: The HO of *H. bramlettei* is an Upper Oligocene GoM marker and dated at 24.870Ma in the Leg 154 research (Table 1). It ranges down into the Middle Eocene (NP15).

***Helicosphaera wilcoxonii* (Gartner, 1971) Jafar & Martini, 1975**

Pl. 3, figs 8–9

1971 *Helicopontosphaera wilcoxonii* Gartner, p. 110, pl. 2, figs. 1–4

1975 *Helicosphaera wilcoxonii* (Gartner, 1971) Jafar & Martini, p. 391

Remarks: The holotype is 10.4μm with a straight, disjunct bar aligned with the minor axis; the flange is extended and with a 'flattened' flange edge at the top. The flange of *H. bramlettei* is pointed and typically shorter.

Occurrence: The HO of *Helicosphaera wilcoxonii* is an Upper Oligocene GoM marker and dated at 25.061Ma in the Leg 154 research (Table 1). It ranges down into the Middle Eocene (NP18).

***Helicosphaera robinsoniae* Bown & Dunkley Jones, 2012**

Pl. 3, figs 10–13

2012 *Helicosphaera robinsoniae* Bown & Dunkley Jones, p. 28, pl. 6, figs. 29–34

Remarks: *Helicosphaera robinsoniae* is a large, subrectangular species with an oblique, quadrate bar and a truncate flange (Table 2). Most specimens range between 10–12μm. It is distinguished from the other two species in this group by its subrectangular outline. *Helicosphaera robinsoniae* has been referred to as "*Helicosphaera disjuncta*" in BP GoM lexicon.

Occurrence: Bown & Dunkley Jones (2012) reported the species restricted to the Lower Oligocene, ranging from upper Zone NP21 to lower Zone NP22. This supports our observations in deep-water GoM wells.

4.4 *Helicosphaera compacta* group

This group includes two taxa that share ovoid outlines, type II interference patterns, and central areas with two holes aligned with longitudinal axis, separated by a conjunct bar (Table 2).

Helicosphaera disrupta* de Kaenel & Bergen, *sp. nov.

Pl. 3, figs 14–15

Derivation of name: From Latin *disruptus* meaning 'separated'.

Diagnosis: A large, ovoid *Helicosphaera* species with a type II interference pattern, a truncate flange, and a central area with a conjunct bar separating two small holes.

Description: A large *Helicosphaera* with a very distinct ovoid outline. Specimens display a type II interference pattern. The flange is truncate, but interrupts an otherwise continuous periphery. A conjunct bar is aligned or somewhat aligned with the minor ellipse axis; a longitudinal medial suture may divide the conjunct bar. The central holes are round and small to medium in size.

Remarks: *Helicosphaera disrupta* was referred to in BP GoM lexicon as "*Helicosphaera* cf. *compacta*." *Helicosphaera compacta* differs by its having a continuous peripheral outline and an Oligocene extinction.

Holotype dimensions: L = 8.8μm; W = 8.0μm

Holotype: Pl. 3, figs 14–15

Type locality: ODP Leg 154, Hole 926B, Ceará Rise, western equatorial Atlantic

Type level: Sample 926B-45-3,15–17cm, Zone NN2, Aquitanian

Occurrence: The HO of *H. disrupta* is a long-standing BP GoM marker. This event falls in Zone NN2 and has

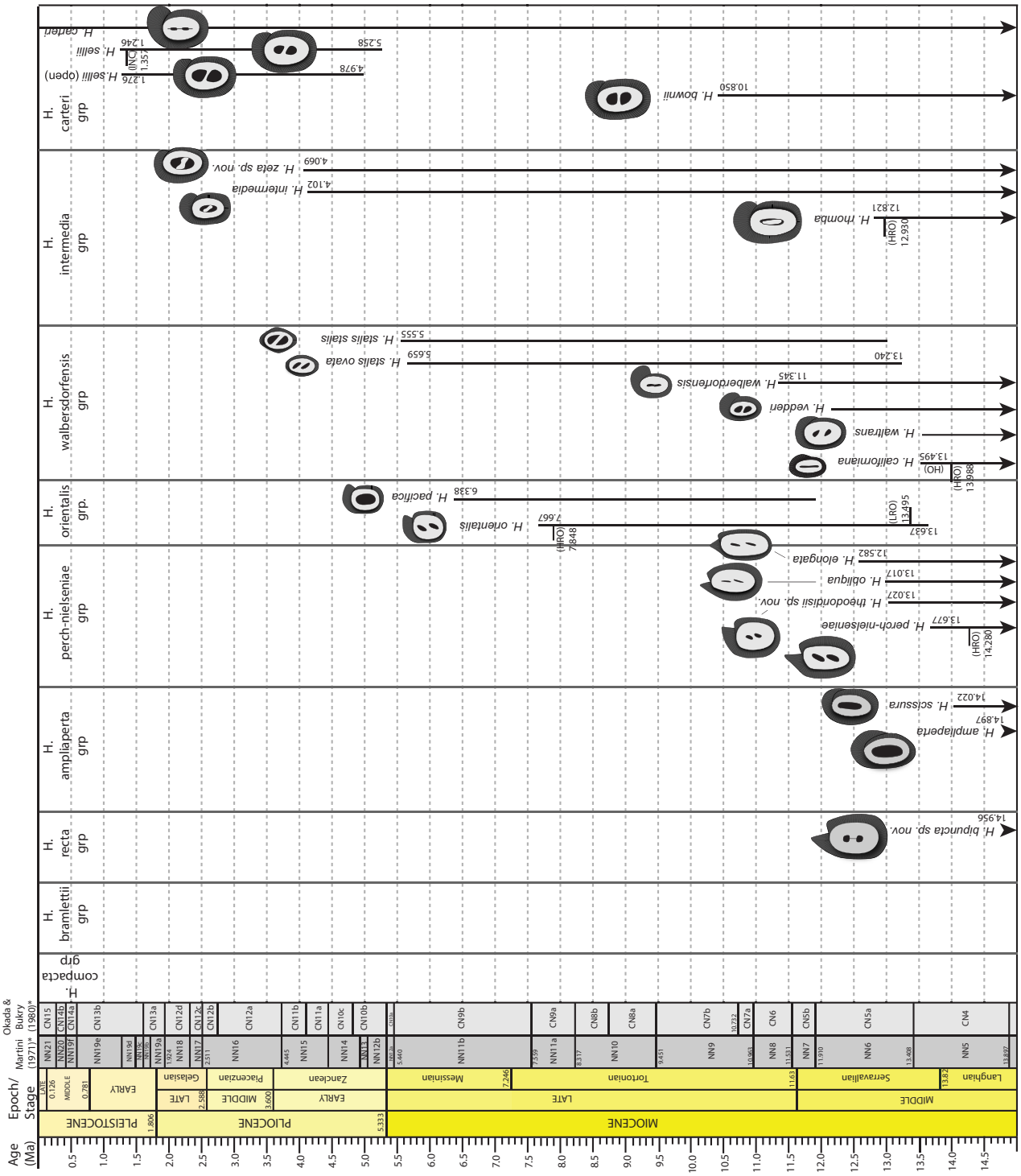


Figure 2: Distribution range chart of *Helicosphaera* species between uppermost Zone NN4 (15.908Ma) and Zone NN21 (latest Langhian to Recent)

been dated at 21.161Ma in the Leg 154 research (Table 1). In Leg 154, the LO was observed in middle Zone NP24 (Figure 3).

***Helicosphaera compacta* Bramlette & Wilcoxon, 1967**

Pl. 3, figs 16–17

1967 *Helicosphaera compacta* Bramlette & Wilcoxon, p. 105, pl. 6, figs. 5–8

Remarks: *Helicosphaera compacta* is a large ovoid form. Its shape is unique among Oligocene *Helicosphaera* and more typical of middle Eocene forms. The holotype is 12.6μm, has a continuous flange, and two small, slightly elongate holes (Table 2). *Helicosphaera disrupta* differs by having a truncate flange.

Occurrence: The HO of *H. compacta* is an upper Oligocene GoM marker and dated at 27.376Ma in the Leg

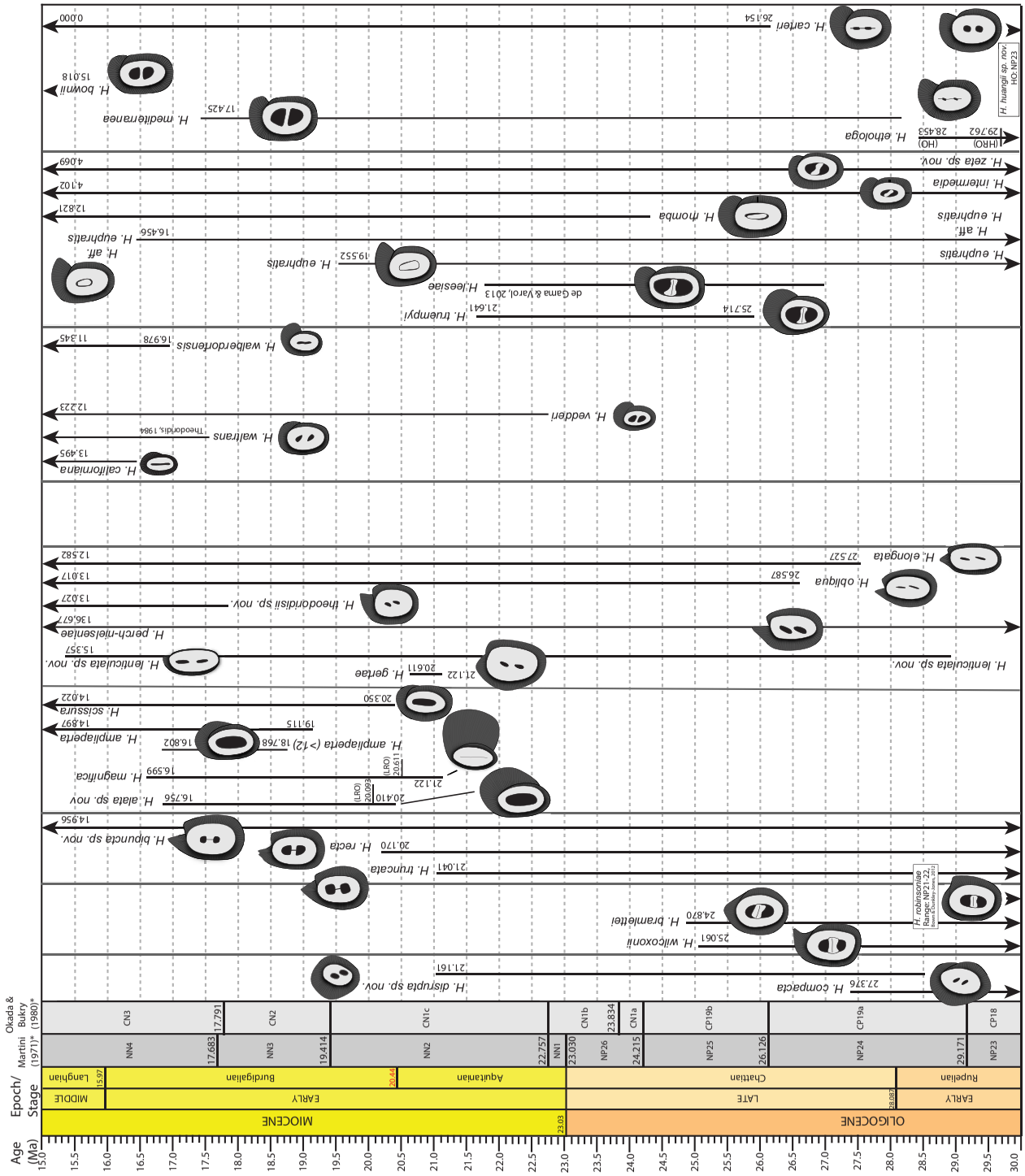


Figure 3: Distribution range chart of *Helicosphaera* species from Figure 2 between the upper Zone NP23 (30.000Ma) and the top of Zone NN5 (15.000Ma; Upper Rupelian to upper Langhian)

154 research (Table 1). It ranges down into the Middle Eocene (NP16).

4.5 *Helicosphaera ampliaperta* group

The four taxa in this group have type II interference patterns and open central areas (Table 2). Two species have greatly extended flanges, but no stratigraphic utility in the deep-water GoM. Conversely, the two forms without greatly extended flanges are long-standing BP GoM markers. The group ranges between upper Zone NN2 to middle Zone NN5.

Helicosphaera magnifica Varol, 1989

Pl. 3, figs 18–28

1989 *Helicosphaera magnifica* Varol, p. 251, pl. 3, figs. 4–9

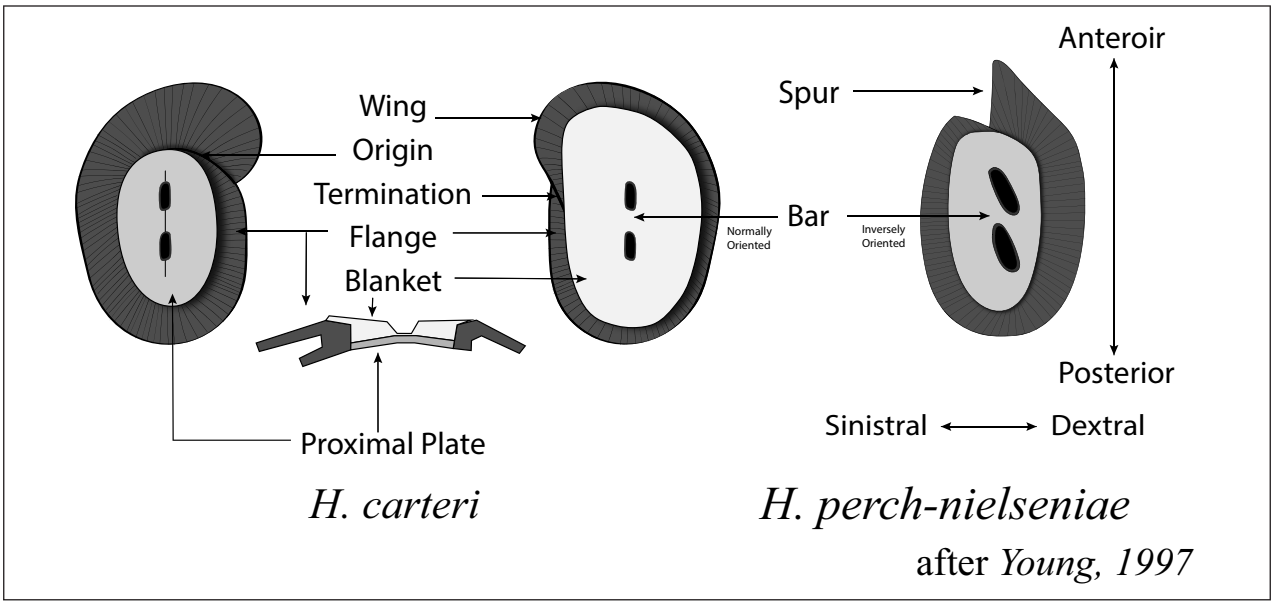


Figure 4: *Helicosphaera* morphology terminology

2008 *Helicosphaera* sp. "A", Denne, p. 237, pl. 1, fig. 11

Remarks: The holotype measures 7.7μm (W = 8.05μm). *Helicosphaera magnifica* is a medium to large species with an extremely extended and curved wing, and a closed central area with a longitudinal slit. The wing does not cover the entire side of the helicolith in early forms of *H. magnifica* whereas it may cover the whole side in later forms (see Plate 3).

Occurrence: *Helicosphaera magnifica* is extremely rare in deep-water GoM wells. It ranges from middle Zone NN2 to lower Zone NN4 in the Leg 154 research. The HO was observed in Sample 925A-9R-6, 140–141cm and dated at 16.599Ma (error 0.020Ma). The LRO was observed in Sample 926B 43X-3, 50–51cm and dated at 20.611Ma (error 0.020Ma). Single specimens were observed in two samples down section: Sample 926B 43X-4, 135–136cm (20.691Ma) and Sample 926B 45X-2, 110–111cm (21.122Ma).

Helicosphaera alata de Kaenel & Boesiger, *sp. nov.*

Pl. 4, figs 1–8

Derivation of name: From Latin *alatus* meaning 'winged'.

Diagnosis: A large to very large elliptical *Helicosphaera* species with a type II interference pattern, a curved flange with an extended wing, and a large open central area.

Description: A large to very large *Helicosphaera* with an elliptical to narrowly elliptical peripheral outline and displaying a type II interference pattern. The curved flange (termination) has great anterior and lateral extension and merges into side of the helicolith in the posterior portion of the specimen to form a wing. The central area is open and its peripheral outline elliptical to narrowly elliptical.

Remarks: The curved flange of *H. alata* exhibits variability in the size of the extended wing. The central opening can be narrow to wide. *Helicosphaera alata* is distinguished from *H. ampliaperta* and *H. scissura* by its extended wing. *Helicosphaera magnifica* has a closed central area. *Helicosphaera alata* was referred to in BP GoM lexicon as *Helicosphaera diademata.*

Holotype dimensions: L = 14.2μm; W = 10.8μm (without flange/wing: L = 10.1μm; W = 7.5μm)

Holotype: Plate 4, figures 1–4

Type locality: ODP Leg 154, Hole 926B, Ceará Rise, western equatorial Atlantic

Type level: Sample 926B-37-3, 15–17cm, Zone NN3, Burdigalian

Occurrence: *Helicosphaera alata* is extremely rare in deep-water GoM wells. It ranges from upper Zone NN2 to middle Zone NN4 in the Leg 154 research. The HO was observed in Sample 925A-10R-1, 20–21cm and dated at 16.756Ma (error 0.004Ma). The LRO was observed in Sample 926C 41X-4, 30–31cm and dated at 20.093Ma (error 0.018Ma). A single specimen was observed in one sample down section: Sample 926B 42X-5, 100–101cm (20.410Ma).

Helicosphaera ampliaperta Bramlette & Wilcoxon, 1967

Pl. 4, figs 9–18

1967 *Helicosphaera ampliaperta* Bramlette & Wilcoxon, p. 105, pl. 6, figs. 1–4

Remarks: Bramlette & Wilcoxon (1967) stated a size range of 7–12μm for the species (holotype is 12.0μm). BP GoM has long utilized the lower Miocene extinctions of both *H. ampliaperta* and 'large' *H. ampliaperta*. Post-merger analyses of deep-water GoM wells, in addition to Leg 154 research, have pinpointed the size of the large morphotype to specimens to greater than 12μm. *Helicosphaera ampliaperta* is distinguished from *H. scissura* by its larger, oval

Plate no.	Species	Structural group	Interference pattern	Outline	Flange	Bar type	Bar angle or pores/slit	Comments
1	*carteri*	*H. carteri*	III	elliptical	curved	conjunct	2 longitudinal pores	Upper Oligocene-Recent
1	*sellii*	*H. carteri*	III	elliptical	curved	conjunct	low angle	Plio-Pleistocene; medium to large holes
1	*bownii*	*H. carteri*	III	elliptical	curved	conjunct	2 pores	Middle Miocene; medium holes
1	*mediterranea*	*H. carteri*	III	elliptical	curved	conjunct	low angle	Lower Mio-Oligocene; medium/large holes
1	*ethologa*	*H. carteri*	III	elliptical	curved	conjunct	2 slits	Lower Oligocene
1	*huangii*	*H. carteri*	III	elliptical	truncate	conjunct	2 pores	Lower Oligocene; medium holes
2	*intermedia*	*H. intermedia*	III	elliptical	curved	disjunct	straight/high angle	thin bar
2	*zeta*	*H. intermedia*	III	elliptical	curved	disjunct	sigmoid/low angle	notched/sigmoid bar
2	*leesiae*	*H. intermedia*	III	elliptical	curved	disjunct	sigmoid/minor	wing or notched flange
2	*rhomba*	*H. intermedia*	III	elliptical	curved	disjunct	straight/high angle	medium thickness bar
2	*euphratis*	*H. intermedia*	III	elliptical	curved	disjunct	straight/high angle	thick bar, rectangular shape
3	*truempyi*	*H. intermedia*	III	elliptical	truncate	disjunct	minor axis	large form w/large center
3	*bramlettei*	*H. bramlettei*	II	elongate	truncate	disjunct	low angle	pointed flange
3	*wilcoxonii*	*H. bramlettei*	II	elongate	truncate	disjunct	low angle	crested flange
3	*robinsoniae*	*H. bramlettei*	II	subrectangular	truncate	disjunct	low angle	quadrate bar in minor axis
3	*disrupta*	*H. compacta*	II	ovoid	truncate	conjunct	two holes	upper Oligocene-lower Miocene
3	*compacta*	*H. compacta*	II	ovoid	continuous	conjunct	two pores	Eocene to “mid” Oligocene
3	*magnifica*	*H. ampliaperta*	II	elliptical	extended	none	slit	
4	*alata*	*H. ampliaperta*	II	elliptical	extended	none	open	large center
4	*ampliaperta*	*H. ampliaperta*	II	elliptical	curved	none	open	large center
4	*scissura*	*H. ampliaperta*	II	elliptical	curved	none	open	small center
5	*bipuncta*	*H. recta*	II	subrectangular	truncate	conjunct	holes	small holes
5	*recta*	*H. recta*	II	subrectangular	truncate	conjunct	low angle	medium holes
5	*truncata*	*H. recta*	II	subrectangular	truncate	conjunct	low angle	large holes
5	*lenticulata*	*H. perch-nielseniae*	II	lenticular	notched	conjunct	oblique slits	very narrow, elongate outline
5	*obliqua*	*H. perch-nielseniae*	II	elliptical	notched	conjunct	oblique slits	
5	*elongata*	*H. perch-nielseniae*	II	subrectangular	notched	conjunct	oblique slits	narrow, elongate outline
6	*perch-nielseniae*	*H. perch-nielseniae*	II	subrectangular	notched	conjunct	oblique slits	
6	*gertae*	*H. perch-nielseniae*	II	elliptical	notched	conjunct	longitudinal slit	large oval form
6	*theodoridisii*	*H. orientalis*	II	subrectangular	truncate	conjunct	oblique slits	middle Miocene
6	*orientalis*	*H. orientalis*	I	rectangular	truncate	conjunct	oblique slits	slits inclined inversely and variable width
6	*pacifica*	*H. orientalis*	I	rectangular	truncate	conjunct	none	dark plate
7	*californiana*	*H. walbersdorfensis*	I	elliptical	curved/large	none	longitudinal slit	narrow opening irregular
7	*walberdorfensis*	*H. walbersdorfensis*	I	elliptical	curved/large	conjunct	oblique slits	narrow opening
7	*waltrans*	*H. walbersdorfensis*	I	elliptical	curved/large	conjunct	low angle	large form w/larger holes
7	*vedderi*	*H. walbersdorfensis*	I	elliptical	curved/small	conjunct	low angle	small form w/large holes
7	*stalis ovata*	*H. walbersdorfensis*	I	elliptical	continuous	conjunct	low angle/sigmoid	small openings
7	*stalis stalis*	*H. walbersdorfensis*	I	rhombic	continuous	conjunct	low angle/straight	large openings

Table 2: Structural groups of *Helicosphaera* based on the interference patterns, peripheral outline, flange and bar morphologies

central opening. The central openings on the two original specimens illustrated by Bramlette & Wilcoxon (1967) occupy 1/4 and 1/3 of the coccolith width.

Occurrence: The stratigraphic ranges of both size morphotypes of *H. ampliaperta* are well constrained in both the GoM and Leg 154 research. *Helicosphaera ampliaperta* ranges from lower Zone NN3 to the top of Zone NN4, dated from 19.115Ma to 14.897Ma (Table 1). As expected, the larger morphotype has a shorter stratigraphic range, which is dated from 18.768Ma to 16.802Ma (Table 1).

Helicosphaera scissura Miller, 1981

Pl. 4, figs 19–28

1981 *Helicosphaera scissura* Miller, p. 433, pl. 3, figs. 10a-c, 11a-b

Remarks: The holotype measures 14.4μm. *Helicosphaera scissura* is distinguished from *H. ampliaperta* and *H. alata* by its narrow central opening. *Helicosphaera magnifica* has a closed center (longitudinal slit). *Helicosphaera californiana* is smaller, has a type I interference pattern, and an extended wing. *Helicosphaera scissura* was referred to in BP GoM lexicon as “small *Helicosphaera ampliaperta*.”

Occurrence: The HO of *H. scissura* is a long standing BP GoM marker, which has been dated at 14.022Ma (Table 1). The LO of *H. scissura* in the Leg 154 research in

Zone NN2 is dated at 20.350Ma (926B-42X-4, 35–37cm; error 0.020Ma).

4.6 *Helicosphaera recta* group

This group includes *Helicosphaera* with sub-rectangular outlines, type II interference patterns, and a central conjunct bar separating two holes (Table 2). The size of the central openings is used to distinguish among the three species in this group. This morphologic feature has stratigraphic utility in an operational sense, as the size of the central openings increase down-section in the lower Miocene. The LO of the group in the Lower Oligocene within Zone NP21 is below the reach of our current research; thus, the appearances of the three species have not yet been differentiated.

Helicosphaera bipuncta* de Kaenel & Bergen, *sp. nov.

Pl. 5, figs 1–5

2008 *Helicosphaerea neorecta,* Denne, p. 235, pl. 1, fig. 7

Derivation of name: From Latin *bi* meaning 'two' and *punctum* meaning 'little hole'.

Diagnosis: A subrectangular *Helicosphaera* species with a type II interference pattern, a truncate flange, and central area with a conjunct bar that separates two small holes.

Description: A large *Helicosphaera* with a subrectangular peripheral outline and a type II interference pattern. The flange is truncate and has a pointed wing-termination. The angle between the wing and the body of the coccolith is broadly acute to orthogonal. The two small central holes are present on either side of a conjunct bar roughly aligned with the minor axis. A longitudinal suture may divide the bar. The central holes are rounded to subrectangular and occupy less than 1/10 the coccolith width.

Remarks: *Helicosphaera bipuncta* has the smallest central openings of the three taxa included in this group. The two specimens illustrated herein (Plate 5, Figs. 1–2 and Figs. 3–5) have the following dimensions respectively: 10.1μm and 9.8μm length, central holes 0.6μm and 0.4μm, and hole to coccolith width ratios of 0.09 and 0.07. Other subrectangular *Helicosphaera* with type II interference patterns possess central slits. The central slits of *H. obliqua* are elongate to strongly elliptical, forming a high angle to the minor ellipse axis.

Holotype dimensions: L = 9.8μm; W = 6.6μm

Holotype: Pl. 5, figs 3–5

Type locality: ODP Leg 154, Hole 925A, Ceará Rise, western equatorial Atlantic

Type level: Sample 925A-9-5, 90–91cm, Zone NN4, Burdigalian

Occurrence: The stratigraphic range of *H. bipuncta* is not yet constrained in the GoM. The extinction of *H. bipuncta* is much younger than the other two species in this group. In Leg 154, the HO was placed in Sample 925D-35H-4, 60–61cm (14.956Ma) near the top of Zone NN4. However, the next occurrence in Sample 925D-35H-6, 95–96cm (15.119Ma) is eight samples down-section and only three specimens were observed in the top 25 samples of its range. Denne (2008) listed the HRO as a 'zonal flag' for zone NN4.

***Helicosphaera recta* (Haq, 1966) Jafar & Martini, 1975**

Pl. 5, figs 6–9

1966 *Helicosphaera seminulum recta* Haq, p. 34, pl. 2, fig. 6; pl. 3, fig. 4

1975 *Helicosphaera recta* (Haq, 1966) Jafar & Martini, p. 391

Remarks: Haq (1966) gave a size range of 7–10μm for the species. He illustrated two specimens, the holotype (L = 8.2μm) and the paratype (L = 10.0μm). The central holes of these two specimens are angular and their sizes 0.75μm and 0.90μm, respectively; they occupy 0.13 of the coccolith width on both specimens. The two specimens illustrated herein have the following dimensions: 9.0μm and 10.7μm length, central holes 1.0μm and 1.2μm, and hole to coccolith width ratios of 0.17 and 0.19. *Helicosphaera recta* has larger central openings than *H. bipuncta* and smaller openings than *H. truncata*. *Helicosphaera recta* and *H. truncata* are thought synonymous by most researchers and one of the heritage companies (Amoco), but their distinction has proven stratigraphic utility with *H. recta* having a younger extinction in both the GoM and Leg 154 research. *Helicosphaera recta* has been referred to as "*Helicosphaera* cf. *recta*" in the BP GoM lexicon.

Occurrence: The HO of *H. recta* is a long-standing BP GoM marker and dated at 20.170Ma in the Leg 154 research (Table 1).

***Helicosphaera truncata* Bramlette & Wilcoxon, 1967**

Pl. 6, figs 10–13

1967 *Helicosphaera truncata* Bramlette & Wilcoxon, p. 106, pl. 6, figs. 13–14.

Remarks: The holotype of *H. truncata* is 13.5μm and has two large, angular central openings (2.2μm) that occupy about 0.24 of the coccolith width. Bramlette and Wilcoxon (1967) gave a size range of 10–15μm for the species. The two specimens illustrated herein have the following dimensions: 11.8μm and 10.4μm length, central holes 1.6μm and 1.8μm, and hole to coccolith width ratios of 0.23 and 0.28. *Helicosphaera truncata* has the largest central openings (> 0.20 of the coccolith width) of the three species placed in this group. *Helicosphaera truncata* is generally larger than both *H. recta* and *H. bipuncta. Helicosphaera truncata* has been referred to as "*Helicosphaera recta*" in BP GoM lexicon.

Occurrence: The HO of *H. truncata* is a long-standing BP GoM marker and dated at 21.041Ma in the Leg 154 research (Table 1).

4.7 *Helicosphaera perch-nielseniae* group

The six species included in this group are characterized by their type II interference patterns and conjunct bars

separating two oblique slits (Table 2). Outlines are subrectangular to elliptical; flange shape and position are variable. Two new species are described.

Helicosphaera lenticulata de Kaenel & Boesiger, *sp. nov.*

Pl. 5, figs 14–16

Derivation of name: From Latin *lenticula* meaning 'shaped like the seed of the lentil'.

Diagnosis: A very narrow, lenticular *Helicospheara* species with a type II interference pattern, notched flange, and central conjunct bar separating two slightly inclined slits.

Description: *Helicosphaera lenticulata* is narrowly elliptical (aspect ratio >2). The flange is truncated and has notched terminations. The central area has two elongate slits, both slightly inclined to the longitudinal axis. The width of the central slits is variable.

Remarks: *Helicosphaera lenticulata* is distinguished from *H. elongata* by its lenticular shape and from *H. obliqua* by being more narrowly elliptical.

Holotype dimensions: L = 6.6μm; W = 3.2μm

Holotype: Pl. 8, figs 14–15

Type locality: ODP Leg 154, Hole 928B, Ceará Rise, western equatorial Atlantic

Type level: Sample 928B-28-5, 30–31cm, Zone NN3, Burdigalian

Occurrence: A range for the species has yet to be established in the GoM. The range of *H. lenticulata* roughly encompasses the Upper Oligocene to Lower Miocene in Leg 154 samples. The LO in Zone NP24 was observed in Sample 925A-38R-2, 98–99cm (28.930Ma), but is unreliable as the next specimen observed was 16 samples higher in Zone NP24 (~ 600kyr). The HO in Sample 925C-37X-1, 140–141cm (15.357Ma; error 0.019Ma) in upper Zone NN4 is more reliable, as specimens were observed in four of the top ten samples of its range.

Helicosphaera elongata Theodoridis, 1984

Pl. 5, figs 17–24

1984 *Helicosphaera elongata* Theodoridis, p. 117, pl. 17, figs. 6–9; pl. 25, fig. 3

Remarks: The holotype is the largest of four specimens illustrated by Theodoridis (1984), which range from 8.3–10.7μm and have aspect ratios between 1.63–1.74. Specimens as small as 6.8μm with an aspect ratio of 2.0 (Pl. 5, figs 17–18) are illustrated herein. Theodoridis (1984) distinguished *H. elongata* by its elongated rectangular outline, pointed wing, and inversely inclined central slits. *Helicosphaera lenticulata* has a narrowly elliptical outline, higher aspect ratio, and is smaller. *Helicosphaera obliqua* has an elliptical outline and *H. perch-nielseniae* has a lower aspect ratio.

Occurrence: *Helicosphaera elongata* ranges from Upper Oligocene to Middle Miocene. The LO in Sample 926B-63X-1, 115–116cm (27.527Ma; error 0.040Ma) within Zone NP24 is fairly accurate (3 of bottom 10 samples). The HO in Sample 926A-26H-4, 112–114cm (11.849Ma) in lower Zone NN7 is most likely redeposited. The HRO is observed in Sample 926A-27H-5, 143.5–145.5cm (12.582Ma; error 0.015Ma) well within Zone NN6 is 37 samples down-section.

Helicosphaera obliqua Bramlette & Wilcoxon, 1967

Pl. 5, figs 25–30

1967 *Helicosphaera obliqua* Bramlette & Wilcoxon, p. 106, pl. 5, figs. 13–14

Remarks: *Helicosphaera obliqua* is one of two elliptical species in this group. The notched flange has a distinct V-shaped wing termination, which is not found on the subrectangular *H. perch-nielseniae* and *H. elongata*. *Helicosphaera lenticulata* is more narrowly elliptical. The holotype is 11.2μm.

Occurrence: In Leg 154, *H. obliqua* ranges from the Upper Oligocene to Middle Miocene. The LO in Sample 926B-60X-2, 25–26cm (26.587Ma; error 0.040Ma) within Zone NP24 is reliable, whereas the HO placed in Sample 926A-27H-5, 14.5–16.5cm (12.477Ma) within Zone NN6 is not reliable and could be redeposited. The next specimen, and the likely HO, is observed in Sample 926A-28H-4, 6–8cm (13.017Ma; error 0.08Ma) is 25 samples down-section, but still within Zone NN6.

Helicosphaera perch-nielseniae (Haq, 1971) Jafar & Martini, 1975

Pl. 6, figs 1–8

1971 *Helicopontosphaera perch-nielseniae* Haq (*pro parte*) p. 116, pl. 10, figs. 5–6; *non* pl. 10, fig. 7

1975 *Helicosphaera perch-nielseniae* (Haq, 1971) Jafar & Martini, p. 391

Remarks: Haq (1971) gave a size of L = 11.5μm and W = 7.5μm for the holotype and a size range of 8.0–11.5μm, but we have used a working definition of 9.0μm for the minimum length. Haq (1971) described the species having "a flare sharply pointed at the end and a closed central area showing impressions of two slit-like furrows". Theodoridis (1984) emended the species to include an asymmetric rectangular outline, a pointed wing (flange) that terminates abruptly near the longitudinal axis, and a type II interference pattern. The angle between the terminal edge of the flange and the shield of *H. perch-nielseniae* is roughly orthogonal, somewhat of a consequence of the subrectangular shape of the species. *Helicosphaera obliqua* differs in being elliptical and having a V-shaped notched apex. *Helicosphaera theodoridisii* is smaller and has a higher aspect ratio; it may have evolved from *H. perch-nielseniae*.

Occurrence: The HRO of *H. perch-nielseniae* is a GoM marker and dated at 14.280Ma in Leg 154 (Table 1). In expanded sections in most deep-water GoM wells, this event is often expressed as an HO. In Leg 154, the HO of *H. perch-nielseniae* was observed in Sample 926A-29–6,

44–46cm (13.677Ma), but is unreliable as the next specimen observed was 13 samples down section (~180kyr). The LO of the species falls within Zone NP22 in the Lower Oligocene.

***Helicosphaera gertae* Bukry, 1981**

Pl. 6, figs 9–12

1981 *Helicosphaera gertae* Bukry, p. 463, pl. 5, figs. 5–13; pl. 6, figs. 1–4

Remarks: Bukry (1981) described *H. gertae* as a large species with a nearly ovoid outline and a median slit along the major axis. The stated size range is 15–22μm with an aspect ratios between 1.17–1.26 for the species. Specimens identified herein as *H. gertae* may have two distinct slits along the median suture (Pl. 6, figs 9–10) or be smaller than 15μm (12.8μm) with aspect ratios up to 1.38 (Pl. 6, figs 11–12). *Helicosphaera perch-nielseniae* is a smaller species with a higher aspect ratio (> 1.4) and two oblique central slits.

Occurrence: The range of *H. gertae* is well constrained and reliable in the Leg 154 research where it is restricted to Zone NN2 and dated from 21.122Ma (928B-33X-1, 70–71cm; 0.020 error) to 20.611Ma (926B-43-3, 50–51cm; 0.020 error). The stratigraphic range is not well established in the GoM.

Helicosphaera theodoridisii* de Kaenel & Boesiger, *sp. nov.

Pl. 6, figs 13–22

1984 *Helicosphaera* cf. *H. orientalis* Theodoridis, p. 118, pl. 17, fig. 10; pl. 18, fig. 1; pl. 25, fig. 5

Derivation of name: In honor of S. Theodoridis for landmark work on the genus *Helicosphaera*.

Description: Subrectangular species of *Helicosphaera* that displays a type II interference pattern. Specimens broaden toward the apex where the flange is located. The flange truncates near the longitudinal axis and is pointed. A conjunct bar spans the central area and separates two oblique slits, which are inclined normally. Size: 5–9μm. The aspect ratio is between 1.26–1.37.

Remarks: *Helicosphaera theodoridisii* is distinguished from *H. perch-nielseniae* by its smaller size and lower aspect ratio, averaging 1.28 among the specimens measured, compared to 1.53 for *H. perch-nielseniae*. *Helicosphaera orientalis* has a type I interference pattern.

Holotype dimensions: L = 7.4μm; W = 5.8μm

Holotype: Pl. 6, figs 15–16

Type locality: ODP Leg 154, Hole 925A, Ceará Rise, western equatorial Atlantic

Type level: Sample 925A-6-2,70–71cm, Zone NN4, Langhian

Occurrence: The stratigraphic range of *H. theodoridisii* is not well established in the GoM. In Leg 154, the HO is placed in Sample 926A-28H-4, 26–28cm within Zone NN6 and dated at 13.027Ma (0.010 error). The species was observed sporadically in samples down into upper Zone NN3.

4.8 *Helicosphaera orientalis* group

This group includes two taxa with Type I interference patterns and rectangular outlines (Table 2).

***Helicosphaera orientalis* Black, 1971**

Pl. 6, figs 23–28

1971 *Helicosphaera orientalis* Black, p. 619, pl. 45.3, fig. 22

1981 *Helicosphaera philippinensis* Müller, p. 429, pl. 1, figs. 7–12

Remarks: The holotype is 4.2μm long. *Helicosphaera orientalis* is a relatively small species with a rectangular outline and truncated flange with a pointed wing termination. The central slits are inclined inversely. *Helicosphaera orientalis* is distinguished from *H. theodoridisii* by its more rectangular outline, the position of the wing termination, and by having a type I interference pattern.

Occurrence: The HRO of *H. orientalis* marks an Upper Miocene stratigraphic horizon in the GoM, along with the HRO of *M. convallis*, dated at 7.848Ma in the Leg 154 research (Table 1). The HO is slightly younger and dated in Leg 154 at 7.667Ma (Table 1), but this event has been observed in only a single deep-water GoM well. The LO has not been established in the GoM, but is placed in upper Zone NN5 in Leg 154, dated at 13.637Ma (926A-29-5, 125–127cm, 0.011 error). The LRO is also in upper Zone NN5 in Leg 154, dated at 13.495Ma (926A-29-4, 10–12cm, 0.004 error).

***Helicosphaera pacifica* Müller & Brönnimann, 1974**

Pl. 6, figs 29–30

1974 *Helicosphaera pacifica* Müller & Brönnimann, p. 661, pl. 1, figs. 1–10

Remarks: The holotype is 4.3μm long. *Helicosphaera pacifica* and *H. orientalis* are both relatively small rectangular species with the same interference patterns and flange morphologies. *Helicosphaera pacifica* is distinguished by its granular central plate.

Occurrence: The HO of *H. pacifica* has been established within Subzone NN11b of the Ain El Beda section (AEB) in Morocco (de Kaenel *in* Krijgsman *et al*., 2004); the HO is in sample AEB 01 in this astronomically-tuned section and dated at 6.388Ma. The species was not recorded in the Leg 154 research. Müller (1981) has a range of NN7 to NN11 for this species.

4.9 *Helicosphaera walbersdorfensis* group

This group includes six taxa characterized by type I interference patterns (i.e. the blanket is confined to the central area so that the flange appears as a continuous, faint cycle in cross polarized light) and curved flanges (Table 2). All but one taxon has an elliptical outline; all but one species has a conjunct bar.

Helicosphaera waltrans Theodoridis, 1984

Pl. 7, figs 1–2

1984 *Helicosphaera waltrans* Theodoridis, p. 124, pl. 13, fig. 2: pl. 20, figs. 5–9; pl. 26, fig. 2

Remarks: Theodoridis (1984) described the species as having a type I interference pattern and differentiated it from *H. vedderi* by its larger size and central openings. The holotype is 11.85μm.

Occurrence: Theodoridis (1984) reported the range of the species from Zone NN4 to NN5. A comparable range was established in the Leg 154, where the species is extremely rare and sporadic in occurrence (single specimens in 3% of samples in range). A reliable stratigraphic range could not be established in deep-water GoM.

Helicosphaera californiana Bukry, 1981

Pl. 7, figs 3–9

1981 *Helicosphaera californiana* Bukry, p. 462, pl. 4, figs. 7–12

Remarks: Bukry (1981) described the species as having a long, narrow slit along the major axis of the central area. The remainder of the taxa included in the *H. walbersdorfensis* group herein have inclined conjunct bars. Theodoridis (1984) considered *H. californiana* synonymous with *H. walbersdorfensis*. The two species can be very difficult to distinguish because: (1) the central area periphery of *H. californiana* appears irregular in cross-polarized light; and (2) the bridge of *H. walbersdorfensis* can be broken (Pl. 7, figs 10–12), resulting in a similar irregularity. *Helicosphaera californiana* is distinguished from *H. scissura* by its interference pattern, narrower central opening, and the irregular outline of the central opening. Bukry (1981) gave a size range of 6–7μm for the species; however, the holotype is 8.0μm long.

Occurrence: The HO of *H. californiana* in uppermost Zone NN5 is dated at 13.495Ma in the Leg 154 research (Table 1). The top of *H. californiana* has been observed at this stratigraphic level in three GoM wells. The HRO of the species is dated at 13.988Ma (Table 1) and used as a datum by BP in the GoM. In Leg 154, the LO was observed in middle Zone NN4.

Helicosphaera walbersdorfensis Müller, 1974

Pl. 7, figs 10–18

1974 *Helicosphaera walbersdorfensis* Müller, p. 392, pl. 2, fig. 15; pl. 4, figs. 35–37, 45–46

1981 *Helicosphaera minuta* Müller, p. 428, pl. 1, figs. 1–6

1989 *Helicosphaera mullerae* Varol, p. 251, pl. 2, fig. 7; pl. 3, figs. 16–21

Remarks: The holotypes of *H. minuta* and *H. mullerae* are differentiated from that of *H. walberdorfensis*. The holotype of H. *walbersdorfensis* is 5.35μm, whereas those of *H. minuta* and *H. mullerae* are 4.0μm and 6.5μm, respectively. They are considered synonymous herein.

Occurrence: *Helicosphaera walbersdorfensis* ranges from Zones NN4 to NN8 in both Leg 154 and the GoM. In Leg 154, the range of the species was dated from 16.978Ma (928B-27H-1,110–112cm, 0.020 error) to 11.345Ma (926B-25H-6, 50–52cm, 0.011 error).

Helicosphaera vedderi Bukry, 1981

Pl. 7, figs 19–21

1981 *Helicosphaera vedderi* Bukry, p. 463, pl. 6, figs. 8–17

Remarks: Theodoridis (1984) distinguished *Helicosphaera vedderi* from both subspecies of *H. stalis* by its smaller wing on the peripheral outline and broader bar; the stratigraphic ranges of the two species are separate. The holotype of *H. vedderi* is 7.5μm long.

Occurrence: A stratigraphic range has not been established for *H. vedderi* in the GoM. The species ranges from Zone NN2 to NN6 in the Leg 154 materials, in which the species is extremely rare and sporadic in both the upper portion of its range from mid Zone NN4 to lower NN6 (< 3% of samples) and below its LRO in Sample 926B-48X-3, 95–96cm (22.227Ma; error 0.020Ma). Single specimens were observed in Sample 926B-48X-6, 10–11cm (22.348Ma) and Sample 926B-36X-6, 100–102cm (22.757Ma).

Helicosphaera stalis ovata Theodoridis, 1984

Pl. 7, figs 22–26

1984 *Helicosphaera stalis ovata* Theodoridis, p. 128, pl. 13, fig. 6; pl. 20, figs. 10–12; pl. 21, figs. 1–7; pl. 26, fig. 6

Remarks: The holotype is 4.9μm long. Theodoridis (1984) differentiated the species from *H. vedderi* by its smaller wing and younger geologic age. *Helicosphaera stalis ovata* is distinguished from *H. stalis stalis* by its elliptical outline and small central openings.

Occurrence: We were unable to establish a reliable stratigraphic range for either subspecies of *H. stalis* in the deep-water GoM. In Leg 154, a reliable LO was established for *H. stalis ovata* in lower Zone NN6 and dated at 13.240Ma (926A-28H-6, 47.5–49.5, 0.019 error). The HO for the subspecies was established in Subzone NN11b based on data from the Ain El Beda section (AEB) in Morocco (de Kaenel *in* Krijgsman *et al*., 2004). The AEB section has been astronomically-tuned and the HO of *H. stalis ovata* was observed in sample AEB 230 and dated at 5.659Ma.

Helicosphaera stalis stalis Theodoridis, 1984

Pl. 7, figs 27–30

1984 *Helicosphaera stalis stalis* Theodoridis, p. 127, pl. 21, figs. 8–12; pl. 26, fig. 5

Remarks: The holotype is 4.5μm long. *Helicosphaera stalis stalis* is distinguished from *H. stalis ovata* by its rhombic outline and large kidney-shaped central openings.

Occurrence: The stratigraphic range established for *H. stalis stalis* is similar to *H. stalis ovata*. In Leg 154, the LO of *H. stalis stalis* was observed in lower Zone NN6 at 13.017Ma (926A-28H-4, 6–8cm); however, this base is tenuous, as single specimens of the subspecies were observed in only 3 of 25 samples at the bottom of its

stratigraphic range (~540kyr). The HO of *H. stalis stalis* was also established within Subzone NN11b in the Ain El Beda section (AEB) in Morocco (de Kaenel *in* Krijgsman *et al*., 2004), where it was observed in sample AEB 255 and dated at 5.555Ma.

4.10 Additional taxa

Genus *Coccolithus* Schwartz, 1894

Coccolithus miopelagicus Bukry, 1971

Pl. 8, figs 1–4

1971 *Coccolithus miopelagicus* Bukry, p. 310, pl. 2, figs. 6–9

1973 *Coccolithus miopelagicus* Bukry. Wise, p. 593, pl. 8, figs. 9–11

Remarks: Wise (1973) limited the size of the species to 13–20μm in his emendation. Several GoM nannofossil biostratigraphers maintain a minimum size of 13μm for the species, whereas a minimum size of 14μm is necessary to place its extinction in sequence in the BP GoM framework. Smaller specimens with relatively broad collars like *C. miopelagicus* are referred to as *C. pelagicus*.

Occurrence: *Coccolithus miopelagicus* ranges from the Eocene to Upper Miocene. Its HO is coeval between the GoM and Leg 154, falling within Zone NN8 and dated at 10.996Ma in Leg 154 (Table 1).

Coccolithus pelagicus (Wallich, 1877) Schiller, 1930

Pl. 8, figs 5–6

1877 *Coccosphaera pelagica* Wallich, p. 348, pl. 17, figs. 1, 2, 5, 8, 8a, 9d, 10d, 11d

1930 *Coccolithus pelagicus* (Wallich, 1877) Schiller, p. 246

Occurrence: *Coccolithus pelagicus* is an extant species that ranges throughout almost the entire Cenozoic. A strong downhole increase of *C. pelagicus* in the Upper Miocene (Subzone NN11b) is utilized as a datum in deep-water GoM and dated at 6.550Ma in the Leg 154 research (Table 1).

Coccolithus pliopelagicus Wise, 1973

Pl. 8, figs 7–10

1973 *Coccolithus pliopelagicus* Wise, p. 593, pl. 8, figs. 1–6

Remarks: *Coccolithus pliopelagicus* is differentiated from C. *pelagicus* and *C. miopelagicus* by its smaller, narrower central collar. (birefringent inner cycle). The holotype is 10.3μm in length and normally elliptical. Wise (1973) gave a size range of 6–13μm for the species. The HO of "small *Coccolithus* cf. *miopelagicus*" is immediately above that of *C. miopelagicus* in the heritage BP GoM framework. Post-merger analyses of deep-water GoM wells demonstrated that this top is actually larger specimens of *C. pliopelagicus* greater than 11.0μm.

Occurrence: The HO of *C. pliopelagicus* (>11μm) is a GoM marker and dated at 10.800Ma in the Leg 154 research (Table 1).

Genus *Cryptococcolithus* Gartner, 1992

Gartner (1992) described the genus for elliptical placoliths with weakly birefringent or non-birefringent shields. *Cryptococcolithus* is differentiated from *Calcidiscus* by its more strongly elliptical shape and the low-birefringence of the distal and proximal shields, of which the proximal shield may be slightly more birefringent.

Cryptococcolithus mediaperforatus (Varol, 1991) de Kaenel & Villa, 1996

Pl. 8, figs 11–16

1991 *Birkelundia mediaperforate* Varol, p. 221, fig. 7, nos. 17–20

1992 *Cryptococcolithus takayamae* Gartner, p. 65, pl. 2, figs. 3a, b

1996 *Cryptococcolithus mediaperforatus* (Varol, 1991) de Kaenel & Villa, p. 124, pl. 2, figs. 13–16

Remarks: *Cryptococcolithus mediaperforatus* has a lenticular central collar and a narrow central area filled by a finely perforate net, as compared to the narrowly elliptical collar and imperforate central area of *C. takayamae*. The two species were not separated in the GoM.

Occurrence: *Cryptococcolithus mediaperforatus* ranges from upper Lower Miocene (NN4) to Lower Pliocene (NN14). In Leg 154, its stratigraphic range is dated from 17.138Ma (928B-27-3, 130–132cm; error 0.019Ma) to 4.644Ma (Table 1). The HO in the GoM is older, being placed in the stratigraphic horizon below the top of *Ceratolithus atlanticus* and the HO of *Ceratolithus apiculus* (see Blair *et al*., 2017), dated at 5.258Ma (Table 1).

Genus *Calcidiscus* Kamptner, 1950

The genus *Calcidiscus* includes elliptical, subelliptical, and circular placolith species. The distal shield is weakly birefringent while the proximal shield is birefringent in cross-polarized light. Most *Calcidiscus* species have a central opening that may be surrounded by a very thin to thick collar. The central area may be open or closed by a net with very fine to medium-sized mesh-like structure.

Calcidiscus premacintyrei Theodoridis, 1984

Pl. 8, figs 17–22

1984 *Calcidiscus premacintyrei* Theodoridis, p. 81, pl. 2, figs. 1–3

Remarks: *Calcidiscus premacintyrei* is distinguished from other *Calcidiscus* species by its elliptical inner tube cycle and central opening.

Occurrence: The HO of *C. premacintyrei* is a long-standing GoM marker and dated at 12.368Ma in the Leg 154 research (Table 1). The LO of *C. premacintyrei* is also utilized for correlation in GoM wells and dated at 17.058Ma in the Leg 154 research (Table 1).

Calcidiscus macintyrei (Bukry & Bramlette, 1969) Loeblich & Tappan, 1978

Pl. 8, figs 23–24

1969 *Cyclococcolithus macintyrei* Bukry & Bramlette, p. 132, pl. 1, figs. 1–3
1978 *Calcidiscus macintyrei* (Bukry & Bramlette, 1969) Loeblich & Tappan, p. 1392
Remarks: The holotype is circular and 11.6μm. Specimens ≥11μm with a thick collar (inner tube cycle) and a medium-sized central opening are included in *C. macintyrei*.

Occurrence: The HO of *C. macintyrei* is a long-standing GoM marker used within the three BP heritage companies in the basal Pleistocene and dated at 1.607Ma (Table 1). The first downhole increase defines the subjacent stratigraphic horizon in the BP heritage framework and is dated at 1.634Ma in the Leg 1545 research (Table 1). In Leg 154, the LO is in uppermost Zone NN6.

Genus *Camuralithus* de Kaenel & Villa, 1996

Camuralithus pelliculathus de Kaenel & Villa, 1996

Pl. 9, figs 1–2

1996 *Camuralithus pelliculathus* de Kaenel & Villa, p. 123, pl. 2, figs. 1–12
Remarks: This genus is monospecific. *Camuralithus pelliculathus* is a medium-sized placolith constructed of three shields. Its diagonal central cross is faint in cross-polarized light, but more discernible in phase contrast.

Occurrence: The LO of *C. pelliculathus* is coeval between the GoM and Leg 154, where it is dated within middle Zone NP25 at 25.384Ma (926B-56X-6, 135–136; 0.037Ma error). The HO is diachronous between Leg 154 and the GoM, dated at 20.998Ma in Leg 154 (Table 1). The HO of the species has been associated with the HO of small *S. delphix* in over 20 deep-water GoM wells - this event is dated at 21.362Ma in the Leg 154 research (Table 1).

Genus *Coronocyclus* Hay, Mohler & Wade, 1966 emended da Gama & Varol, 2013

The genus was emended by da Gama & Varol (2013) to include a variety of outlines. Although reliable stratigraphic events were established for some of the taxa in the Leg 154 research, the genus has limited stratigraphic utility in the GoM.

Coronocyclus baileyi da Gama & Varol, 2013 emend. de Kaenel & Bergen

Pl. 9, figs 3–4

2013 *Coronocyclus baileyi* da Gama & Varol (*pro parte*), p. 5, pl. 3, figs. 13–15; *non* pl. 4, figs. 3–4
Emended diagnosis: An elliptical species of *Coronocyclus* species with a large central area and a very narrow rim (< 0.7μm).

Remarks: The original diagnosis of *C. baileyi* characterized it as an "elliptical species of *Coronocyclus*." The Upper Miocene holotype (NN9) has a very narrow shield. Da Gama & Varol (2013) did not illustrate specimens with broader rims. *Coronocyclus mesostenos* is described herein for such forms.

Occurrence: *Coronocyclus baileyi* was not differentiated from *C. mesostenos* in the Leg 154 research. Da Gama & Varol (2013) gave a range of Zone NN4-10 for the species.

Coronocyclus mesostenos de Kaenel & Boesiger, *sp. nov.*

Pl. 9, figs 5–6

1998 *Coronocyclus nitescens* elliptical Young, pl. 8.5, figs 14–15
non 2013 *Coronocyclus baileyi* da Gama & Varol (*pro parte*), pl. 4, figs. 3–4, pl.5, figs. 13–15
Derivation of name: From Greek *stenos* meaning 'narrow' and *meso* meaning 'middle'.

Diagnosis: An elliptical *Coronocyclus* species with a wide central area and a narrow to broad shield.

Remarks: *Coronocyclus mesostenos* has a large central area. Shield width is >0.7μm. In contrast, *Coronocyclus baileyi* has a very narrow shield (<0.7μm).

Holotype dimensions: L = 6.40μm; Shield width (a) = 1.00μm

Holotype: Pl. 9, fig. 6

Type locality: ODP Leg 154, Hole 928A, Ceará Rise, western equatorial Atlantic

Type level: Sample 928A-26-2,110–112cm, Zone NN4, Burdigalian

Occurrence: *Coronocyclus mesostenos* has no proven stratigraphic utility in the GoM, although it is present in the Eocene to Middle Miocene. In Leg 154, an HO has been established in Zone NN6 and dated at 12.465Ma (Sample 926A-27H-4, 146.5–148.5cm; error 0.028Ma).

Coronocyclus nitescens (Kamptner, 1963) Bramlette & Wilcoxon, 1967

Pl. 9, figs 7–10

1963 *Umbilicosphaera nitescens* Kamptner, p.187, pl. 1, fig. 5; text-figs. 37a-c
1967 *Coronocyclus nitescens* (Kamptner, 1963) Bramlette & Wilcoxon, p. 103, pl. 1, fig. 4; pl. 5, figs. 7–8
2013 *Coronocyclus nitescens latus* da Gama & Varol, p. 5, pl. 3, figs. 9–12; pl. 4, fig.1
Remarks: There is variation in both size and shield width of this species. Da Gama & Varol (2013) described the subspecies C. *nitescens latus* for those with wider shields, but this distinction was not made in the analyses of deep-water GoM wells or the Leg 154 research. The size of *C. nitescens* may have stratigraphic utility in the GoM.

Occurrence: *Coronocyclus nitescens* ranges from Lower Eocene to upper Middle Miocene. In Leg 154, a very reliable HO was established for the species in upper Zone NN6 and dated at 12.125Ma (926A-27H-1, 22–24cm; error 0.072Ma). In Leg 154, the HO of larger specimens (>9μm) has been dated at 15.258Ma (925D-36H-2, 55–57cm; error 0.020Ma) and the HRO at 16.018Ma (925C-38H-5, 55–56cm; error 0.020Ma), both falling within Zone NN4. In the GoM, the HO of these larger

forms has been observed in middle Zone NN4, roughly equivalent to the HRO in the research data.

Genus *Cyclicargolithus* Bukry, 1971

Cyclicargolithus bukryi Wise, 1973

Pl. 9, figs 11–13

1973 *Cyclicargolithus bukryi* Wise, p. 594, pl. 9, figs. 1–4
2008 "*Cyclicargolithus minutus*" Denne, p. 238, pl. 2 fig. 4

Remarks: Wise (1973) described the species as a "subcircular placolith constructed of two shields bright in cross-polarized light which exhibit a moderate to wide central area." When comparing the species to *C. floridanus*, he remarked about *C. bukryi* differing by having a subcircular outline with an eccentricity greater than 1.1 and medium to large elliptical central areas that occupy 50% or more of the width. It is not possible to make precise measurements from the light photomicrographs of the holotype of *C. bukryi* and the distal shield of the paratype (fig. 4) is partially damaged. The two specimens illustrated by Wise (1973) are subcircular (AR holotype ~ 1.07) to broadly elliptical (AR paratype 1.16), but the central area sizes do not measure ≥ 50% of the coccolith width (CA 20–25%). Wise (1973) also gave a size range for the species of 6–8mm. In the GoM, *C. bukryi* has been retained for smaller specimens (3–6μm), but are similar to the holotype and paratype by being subcircular to broadly elliptical (AR 1.05–1.10) and having medium-sized central areas (CA 25–50%). Denne (2008) used the informal epithet "*Cyclicargolithus minutus*" for these forms. *Cyclicargolithus bukryi* has been referred to as *Cyclicargolithus* (rim = center) in BP GoM lexicon.

Occurrence: Five events attributed to *C. bukryi* are utilized as BP marker events in deep-water GoM wells. All five events were dated in the Leg 154 research (Table 1) with the: (1) HO at 12.989Ma; (2) HRO at 13.706Ma; (3) first downhole abundance increase at 14.042Ma; (4) top acme at 14.378Ma; and (5) base acme at 14.539Ma. The base acme event is a 'heads-up' for picking the top of Zone NN4. The LO of the species was observed in Zone NN4 in both Leg 154 and the GoM.

Genus *Reticulofenestra* Hay, Mohler & Wade, 1966

Two species utilized in Miocene GoM biostratigraphy are described herein.

Reticulofenestra pospichalii de Kaenel & Bergen, *sp. nov.*

Pl. 9, figs 14–16

Derivation of name: In honor of nannofossil biostratigrapher Jim Pospichal (Bugware Inc., Tallahassee, FL, USA).

Diagnosis: A small, circular to slightly subcircular early Middle Miocene *Reticulofenestra* species with a large central area and narrow rim.

Description: A small circular to slightly subcircular placolith with a very narrow rim. The rim exhibits a faint 1st order white birefringence and appears smooth in cross-polarized light. The central area is equal to or greater than one-half the coccolith diameter. Size: 3–5μm.

Remarks: *Reticulofenestra pospichalii* is reminiscent of the Late Miocene species, *R. rotaria*. It has a narrower rim and larger central area than small specimens of *R. rotaria*. In the GoM, the stratigraphic ranges of these two species are separated by about 6.6 million years. *Cyclicargolithus bukryi* occurs with *R. pospichalii* and is roughly the same size, but that species is subcircular to broadly elliptical and has a broader rim. *Coronocyclus* has a serrate rim.

Holotype dimensions: L = 4.80μm; Aspect Ratio 1.02; CA = 50%

Holotype: Pl. 9, figs 14–15

Type locality: South Trinidad, from Bolli (1957)

Type level: Sample PJ260, *Globigerinetella insueta* Zone, Cipero Formation, Zone NN4, Langhian

Occurrence: *Reticulofenestra pospichalii* ranges from Zones NN4 to NN5. The HO of this distinct but very rare species is a GoM marker and dated at 13.885Ma in Leg 154 (Table 1) and restricted to zone NN5 in this research (Table 1).

Reticulofenestra kahniae de Kaenel & Bergen, *sp. nov.*

Pl. 9, figs 17–20

Derivation of name: In honour of nannofossil biostratigrapher Alicia Kahn (Chevron, Houston, TX, USA).

Diagnosis: A medium to large, circular to subcircular *Reticulofenestra* species with a medium-sized central area.

Description: A circular to subcircular, medium to large placolith with an open central area. The central area is moderate in size, occupying between 25–50% of the coccolith width. The rim exhibits a 1st order white birefringence typical of the genus *Reticulofenestra* and is constructed of numerous elements. Size: 5–10μm.

Remarks: Larger specimens of *R. kahniae* greater than 8μm are distinct in Lower to Middle Miocene sediments in the GoM and Leg 154. Smaller specimens between 5–8μm have been differentiated in both the GoM and Leg 154; however, some uncertainty remains with their morphologic variation, especially gradations into smaller birefringent circular to subcircular placoliths with open central areas and the genus *Cyclicargolithus*. *Reticulofenestra kahniae* has incorrectly been referred to as *Reticulofenestra gartneri* in BP GoM lexicon, due to its size and subcircular outline.

Holotype dimensions: L = 8.10μm; Aspect Ratio 1.07; CA = 42%.

Holotype: Pl. 9, figs 19–20

Type locality: South Trinidad, Bolli (1957)

Type level: Sample PJ260, *Globigerinetella insueta* Zone, Cipero Formation, Zone NN4, Langhian

Occurrence: The HO of large *R. kahniae* (>8μm) is a marker horizon in the GoM, where it has been associated with the HO of *H. ampliaperta* and the top of Zone NN4 in over a dozen deep-water wells. This horizon has

been dated at 14.897Ma (Table 1). In Leg 154, the HO of large specimens greater than 8μm has been placed in Sample 925D-37H-2, 85–87cm and dated at 15.657Ma (error 0.020Ma). The HO of specimens less than 8μm has been associated with the HO of *D. musicus* in over a dozen deep-water GoM wells and dated at 13.067Ma in Leg 154 (Table 1). The LO of the species is in lower Zone NN3 in Leg 154.

Genus *Dictyococcites* Black, 1967, emended Backman, 1980

Backman (1980) stressed the distinction of *Dictyococcites* from the genus *Reticulofenestra*. His emended diagnosis of *Dictyococcites* is "elliptic placoliths with a closed central area in line with the distal shield." Such central areas flush with the distal surface typically exhibit a 1st order white birefringence, although higher order colors are possible in thicker and/or larger specimens. This is opposed to the thin and delicate central proximal shields of *Reticulofenestra*, which are faintly birefringent and often not preserved. The extinctions of the three elliptical, medium to large species considered herein are utilized as markers in the GoM Basin. In cross-polarized light, their central areas are filled by a plate that displays a 1st order white birefringence and appears surrounded by a narrow distal collar. The three taxa are easily distinguished from each other by the arrangement or absence of small central area perforations, but their classification is complicated.

Two binomials are commonly-used in the GoM for two Miocene species whose extinctions bracket the base of the Middle Miocene, *Reticulofenestra lockeri* and *Reticulofenestra daviesii*. The former species has been attributed to specimens with imperforate central plates, whereas the latter to those that also possess a single cycle of small perforations around their central plate peripheries. We refer both of these taxa to *Dictyococcites* and also do not believe that either species name is applicable. Instead, *Dictyococcites albitectus* and *Dictyococcites onustus* are proposed, the former described as new herein. The extinction of the third species, one with a central plate pierced by numerous small perforations, is utilized as marker in the Lower Oligocene. *Dictyococcites gartneri* is introduced as a new combination for this Eocene-Oligocene species; The binomial *Reticulofenestra gartneri* has been used by some specialists, including BP, in the GoM Neogene.

Dictyococcites albitectus de Kaenel & Bergen, *sp. nov.*

Pl. 9, figs 21–23

non 1970 *Reticulofenestra lockeri* Müller, p. 116, pl. 6, figs. 3–5; pl. 7, fig. 4

2008 *Reticulofenestra lockeri*, Denne, p.238, pl. 1, fig. 12

Derivation of name: From Latin *albus* meaning 'white' and *tectus* meaning 'cover'.

Diagnosis: A medium to large, broadly to normally elliptical *Dictyococcites* species with a medium-sized central area filled by an imperforate plate exhibiting a 1st order white birefringence.

Description: A medium to large, broadly to normally elliptical placolith. The entire coccolith exhibits a faint 1st order white birefringence. The rim appears smooth in cross-polarized light due to the high number of elements. A narrow tube cycle (0.5–1.0μm wide) connects the two shields and appears as a collar around the central area. The central area is filled by an imperforate plate flush with the distal surface. It occupies about one-quarter to one-third of the coccolith width. Size: 6–9μm.

Remarks: *Dictyococcites albitectus* has been referred to as *Reticulofenestra lockeri* in the BP GoM lexicon. *Reticulofenestra lockeri* was derived from the common GoM usage, but this species was described as having a perforate central area. The two electron photomicrogaphs of *R. lockeri* (pl. 6, fig. 3; pl. 7, fig. 4) illustrated by Müller (1970) clearly show a perforate central area, but the central perforations are not clear in either light photomicrograph of the holotype (pl. 6, figs. 4–5). *Dictyococcites albitectus* is distinguished from other members of the genus by its relatively large imperforate central plate.

Holotype dimensions: L = 8.60μm; Aspect Ratio 1.13; CA = 26%

Holotype: Pl. 9, figs 22–23

Type locality: ODP Leg 149, Hole 900A, eastern equatorial Atlantic

Type level: Sample 49-3, 113–114cm, Zone NP24, Upper Oligocene

Occurrence: *Dictyococcites albitectus* ranges from the Upper Eocene (NP18) through lower Middle Miocene (NN4). The HO of this species has been utilized as a GoM marker and dated at 15.657Ma in the Leg 154 research (Table 1).

Dictyococcites gartneri (Roth & Hay, 1967) de Kaenel & Bergen, comb. nov.

Pl. 9, figs 24–27

1967 *Reticulofenestra gartneri* Roth & Hay, in Hay, Mohler, Roth, Schmidt & Boudreaux, p. 449, pl. 7, fig 1

Remarks: In BP GoM lexicon, *Dictyococcites gartneri* has been referred to as *Reticulofenestra lockeri* 'perforate grill' and and also thought to be a new species (*Dictyococcites confossitectus*). *Reticulofenestra gartneri* was diagnosed as a broadly elliptical species with a central grille perforated by about 120 small holes. The lower Oligocene holotype, an electron photomicrograph in distal view, has a central area perforated throughout by numerous small holes. The species is transferred to *Dictyococcites* herein because the finely-perforate central plate of the holotype appears flush with the distal surface. We believe the central area exhibits a 1st order white birefringence and would not be likely preserved in its entirety on the holotype if it were thin and delicate (as in *Reticulofenestra*). This finely perforate central plate and its breadth (CA is 20–45%) distinguishes it from other *Dictyococcites* species. Our concept

of the species includes broadly to normally elliptical specimens. Length 5–10μm.

Occurrence: *Dictyococcites gartneri* ranges from the Lower Eocene (NP12) through Lower Oligocene (NP23). The HO of this species has been utilized as a GoM marker and dated at 30.431Ma in the Leg 154 research (Table 1).

***Dictyococcites onustus* Perch-Nielsen, 1971**

Pl. 9, figs 28–30

non 1968 *Stradnerius daviesi* Haq, p. 32, pl. 4, figs. 4–5

1971 *Dictyococcites onustus* Perch-Nielsen, p. 29, pl. 20, figs. 3, 4; Pl. 61, figs. 28, 29

Remarks: *Dictyococcites onustus* has been referred to as *Reticulofenestra lockeri* 'cycle of perfs' in the BP GoM lexicon. This species is often conferred to *Reticulofenestra daviesi* by GoM specialists. *Reticulofenestra daviesi* has a finely-perforate central plug surrounded by a cycle of large holes separated by radial bars; the extinction of this species has been observed in the basal Oligocene (lower Zone NP21) of the GoM by BP. *Dictyococcites onustus*, also based on an Eocene holotype, is well illustrated by Perch-Nielsen (1971) and represents the BP concept of this Lower Miocene GoM marker. It is distinguished from other members of the genus by having a cycle of small holes at its central area periphery.

Occurrence: *Dictyococcites onustus* ranges from the Lower Eocene (NP12) through Lower Miocene (NN4). The HO of this species has been utilized as a GoM marker and dated at 16.018Ma in the Leg 154 research (Table 1).

5. Depository

The slides and samples are stored in the micropaleontological collections of the Natural History Museum in Basel (NMB) in Switzerland. Also curated at the NMB are the samples of the foraminifera collections of H.M. Bolli (1957), which have been used to describe some new species. Type material from DSDP and ODP cores are also stored at the Bremen Core Repository (BCR; Germany) and at College Station Repository (USA). Nannofossil stratigraphic range charts are available from the PANGAEA web database (www.pangaea.de).

Acknowledgments

We are grateful to BP GoM Exploration for their support and encouragement in the publication of this research as well as Graham Vinson, Liz Jolley, and John Farrelly. We are appreciative of the BP GoM teams in Exploration and Production. These groups were fundamental in integration and application of these biostratigraphic events for subsurface description. The authors would like to also thank BP for its financial support of the ODP Leg 154 sampling and research as well those involved with the acquisition, preparation and analyses of materials involved in this study. We're also grateful to the Integrated Ocean Drilling Program for the use of ODP Leg 154 materials. Our gratitude is extended to Drs. Richard Denne and Jeremy Young for reviewing this manuscript. Of course, we'd like to thank the authors' families for their patience and support as these five papers were concurrently written and reviewed. We would like to thank Walter Hale at the IODP Bremen Core Repository (BCR) for the help in sampling the Leg 154 cores. We also thank Diane and Line de Kaenel for helping to process the ODP samples.

References

Aubry, M.-P. 1990. Handbook of Cenozoic Calcareous Nannoplankton. *Book 4: Heliolithae (Helicoliths, Cribriliths, Lopadoliths, and others)*. New York: Micropaleontology Press, 381pp.

Backman, J., 1980. Miocene-Pliocene nannofossils and sedimentation rates in the Hatton-Rockall Basin, NE Atlantic Ocean. *Stockholm Contributions in Geology*, **36**(1): 1–91.

Bergen, J.A., Truax III, S., de Kaenel, E., Blair, S., Browning, E., Lundquist, J., Boesiger, T., Bolivar, M. & Clark, K. 2017 (in prep). BP Gulf of Mexico Neogene Astronomically Tuned Time Scale.

Bergen, J., Truax, S., de Kaenel, E., Boesiger, T., Gamber, J., Lundquist, J. & Febo, L. 2009. Microfossil definition of the Oligocene-Miocene boundary and its application in the Gulf of Mexico. *In*: *Geologic Problem Solving with Microfossils II*, University of Houston, Houston TX, USA, March 2009. Abstracts, 21–22.

Blair, S., Bergen, J., de Kaenel, E., Browning, E. & Boesiger, T. 2017. Upper Miocene-Lower Pliocene taxonomy and stratigraphy in the circum North Atlantic Basin: radiation and extinction of Amauroliths, Ceratoliths, and the *D. quinqueramus* lineage. *Journal of Nannoplankton Research*, **37**(2/3): 113–144.

Bolli, H.M. 1957. Planktonic foraminifera from the Oligocene-Miocene Cipero and Lengua Formations of Trinidad, B.W.I. *Bulletin of the American Museum of Natural History*, **215**: 97–123.

Bown, P.R. & Dunkley Jones, T. 2012. Calcareous nannofossils from the Paleogene equatorial Pacific (IODP Expedition 320 Sites U1331–1334). *Journal of Nannoplankton Research*, **32**(2): 3–51.

Bown, P.R. 2005. Paleogene calcareous nannofossils from the Kilwa and Lindi areas of coastal Tanzania (Tanzania Drilling Project 2003–4). *Journal of Nannoplankton Research*, **27**(1): 21–95.

Bramlette, M.N. & Wilcoxon, J.A. 1967. Middle Tertiary calcareous nannoplankton of the Cipero Section, Trinidad, W.I. *Tulane Studies in Geology and Paleontology*, **5**(3): 93–132.

Bukry, D. 1981. Pacific coast coccolith stratigraphy between Point Conception and Cabo Corrientes, Deep Sea Drilling Project Leg 63. *In*: Yeats, R.S., Haq, B.U., *et al., Initial Reports of the DSDP*, **63**: Washington D.C. (U.S. Government Printing Office): 445–471.

Bukry, D. & Bramlette M.N. 1969. Some new and stratigraphically useful calcareous nannofossils of the Cenozoic. *Tulane Studies in Geoloxy and Paleontology,* **7**: 131–142.

Bukry, D. & Percival, S.F. 1971. New Tertiary calcareous nannofossils. *Tulane Studies in Geology and Paleontology,* **8**: 123–146.

Da Gama, R.O.B.P. & Varol, O. 2013. New Late Oligocene to Miocene Species. *Journal of Nannoplankton Research*, **33**(1): 1–12.

De Kaenel, E. & Bergen, J. 2008. Middle Miocene lineages in the calcareous nannofossil genus *Discoaster*. *In*: *INA 12 abstracts*, Lyon, France, September, 2008: 47.

De Kaenel, E. & Villa, G. 1996. Oligocene–Miocene calcareous nannofossil biostratigraphy and paleoecology from the Iberia Abyssal Plain. *In*: R.B. Whitmarsh, D.S. Sawyer, A. Klaus & D.G. Masson (Eds). *Proceedings of the ODP, Scientific Results*, **149**: College Station, TX (Ocean Drilling Program), 79–145.

De Kaenel, E. & Villa, G. 2010. Nannofossil definition of the Oligocene/Miocene boundary at Lemme-Carrosio (Italy). *In*: *INA 13 abstracts*, Yamagata, Japan September 2010: 33.

De Kaenel, E., Bergen, J., Blair, S., Boesiger, B. & Browning, E. 2017. Uppermost Oligocene to Middle Miocene *Discoaster* and *Catinaster* taxonomy and stratigraphy in the circum North Atlantic Basin: Gulf of Mexico and ODP Leg 154. *Journal of Nannoplankton Research*, **37**(2/3): 215–244.

Denne, R.A. 2008. Utilizing abundance changes of new and non-standard calcareous nannofossil taxa to increase biostratigraphic resolution in expanded continental margin deposits: Examples from the Middle and Lower Miocene of the Gulf of Mexico. *Gulf Coast Association of Geological Societies Transactions*, **58**: 227–239.

Gartner, S. Jr. l967. Calcareous nannofossils from Neogene of Trinidad, Jamaica, and Gulf of Mexico. *The University of Kansas Paleontological Contributions,* Paper **29**: 1–7.

Gartner, S. Jr. 1992. Miocene nannofossil chronology in the North Atlantic, DSDP Site 608. *Marine Micropaleontology,* **18**: 307–331.

Gradstein, F.M., Ogg, J.G., Schmitz, M.D. & Ogg, G.M. (Eds) 2012. *The Geologic Time Scale 2012*. Elsevier Science BV, Oxford, UK, Amsterdam, 2012: 1144pp.

Haq, B.U. 1966. Electron microscope studies on some Upper Eocene calcareous nannoplankton from Syria. *Stockholm Contributions in Geology*, **15**(3): 23–37.

Haq, B.U. 1971. Paleogene calcareous nannoflora. Part III: Oligocene of Syria. *Stockholm Contributions in Geology*, **25**(3): 99–127.

Hay, W.W., Mohler, H.P., Roth, P.H., Schmidt, R.R. & Boudreaux, J.E. 1967. Calcareous nannoplankton zonation of the Cenozoic of the Gulf Coast and Caribbean-Antillean area, and transoceanic correlation. *In*: Symposium on the geological history of the Gulf of Mexico, antillean Caribbean region. *Transactions of the Gulf Coast Association of Geological Societies*, **17**: 428–480.

Krijgsman, W., Gaboardi, S., Hilgen, F.J., Iaccarino, S., de Kaenel, E. van der Laan, E. 2004. Revised astrochronology for the Ain el Beida section (Atlantic Morocco): No glacio-eustatic control for the onset of the Messinian Salinity Crisis. *Stratigraphy*, **1**(1): 87–101.

Laskar, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A.C.M. & Levrard, B. 2004. A long term numerical solution for the insolation quantities of the Earth. *Astronomy & Astrophysics*, **428**: 261–285.

Lourens, L.J., Antonarakou, A., Hilgen, F.J., van Hoof, A.A.M., Vergnaud-Grazzini, C. & Zachariasse, W.J. 1996. Evaluation of the Plio-Pleistocene astronomical timescale. *Paleoceanography*, **11**(4): 391–413.

Lourens, L.J., Hilgen, F.J., Shackleton, N.J. Laskar, J. & Wilson, D. 2004. The Neogene Period. *In*: F.M. Gradstein, J.G. Ogg & A.G. Smith (Eds). *A Geological Time Scale 2004*. Cambridge University Press, Cambridge, 409–440.

Martini, E. 1971. Standard Tertiary and Quaternary calcareous nannoplankton zonation. *In*: A. Farinacci (Ed.). *Proceedings of the Second Planktonic Conference Roma 1970*. Edizioni Tecnoscienza, Rome, **2**: 739–785.

Martini, E. & Bramlette, M.N. 1963. Calcareous nannoplankton from the experimental Mohole drilling. *Journal of Paleontology*, **37**(4): 845–856.

Müller, C. 1970. Nannoplankton-Zonen der Unteren Meeresmolasse Bayerns. *Geologica Bavarica*, **63**: 107–118.

Müller, C. 1981. Beschreibung neuer *Helicosphaera*-Arten aus dem Miozän und Revision biostratigraphischer Reichweiten einiger Neogener Nannoplankton-Arten. *Senckenbergiana lethaea,* **61**(3/6): 427–435.

Okada, H. & Bukry, D. 1980. Supplementary modification and introduction of code numbers to the low-latitude coccolith biostratigraphic zonation (Bukry, 1973; 1975). *Marine Micropaleontology,* **5**: 321–325.

Pälike, H., Frazier, F. & Zachos, J.C. 2006. Extended orbitally forced palaeoclimatic records from the equatorial Atlantic Ceará Rise. *Quaternary Science Reviews*, **25**: 3138–3149.

Perch-Nielsen, K., 1971. Elektronenmikroskopische Untersuchungen an Coccolithen und verwandten formen aus dem Eozän von Dänemark. *K. Danske Videnshabernes*, *Biol. Skrifter*, **18**(3): 1–75.

Perch-Nielsen, K. 1985. Cenozoic calcareous nannofossils. *In*: H.M. Bolli, J.B. Saunders & K. Perch-Nielsen (Eds). *Plankton Stratigraphy*. Cambridge University Press, Cambridge, 427–554.

Roth, P.H. 1970. Oligocene calcareous nannoplankton biostratigraphy. *Eclogae Geologicae Helvetiae,* **63**: 799–881.

Roth, P.H., Franz, H.E. & Wise, S.W., Jr. 1971. Morphological study of selected members of the genus *Sphenolithus* Deflandre (Incertae Sedis, Tertiary). *In*: A. Farinacci (Ed.). *Proceedings of the Second Planktonic Conference Roma 1970*. Edizioni Tecnoscienza, Rome, **2**: 1099–1119.

Shackleton, N.J. & Crowhurst, S. 1997. Sediment fluxes based on an orbitally tuned time scale 5Ma to 14Ma, Site 926. *In*: N.J. Shackleton, W.B. Curry, C. Richter & T.J. Bralower (Eds). *Proceedings of the ODP, Scientific Results*, **154**: College Station, TX (Ocean Drilling Program), 69–82.

Theodoridis, S. 1984. Calcareous nannofossil biozonation of the Miocene and revision of the helicoliths and discoasters. *Utrecht Micropaleontological Bulletins,* **32**: 1–271.

Varol, O. 1989. Calcareous nannofossil study of the central and western Solomon Islands. *In:* J.G. Vedder & T.R. Bruns (Eds). *Geology and offshore resources of Pacific island arcs Solomon Islands and Bougainville, Papua and New Guinea Regions:* Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources, *Earth Sciences Ser*ies, **12**: 239–268.

Varol, O. 1991. New Cretaceous and Tertiary calcareous nannofossils. *Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen,* **182**: 211–237.

Wise, S.W., Jr. 1973. Calcareous nannofossils from cores recovered during Leg 18, Deep Sea Drilling Project: biostratigraphy and observations of diagenesis. *In*: L.D. Kulm, R. von Huene, *et al*. *Initial Reports of the DSDP,* **18**: Washington D.C. (U.S. Government Printing Office): 569–615.

Young, J.R. 1998. Neogene. *In:* P.R. Bown (Ed.). *Calcareous Nannofossil Biostratigraphy*. Kluwer Academic, London, 225–265.

Young, J.R., Bergen, J.A., Bown, P.R., Burnett, J.A., Fiorentino, A., Jordan, R.W., Kleijne, A., van Niel, B.E., *et al*. 1997. Guidelines for coccolith and calcareous nannofossil terminology. *Palaeontology*, **40**: 875–912.

Plate 1

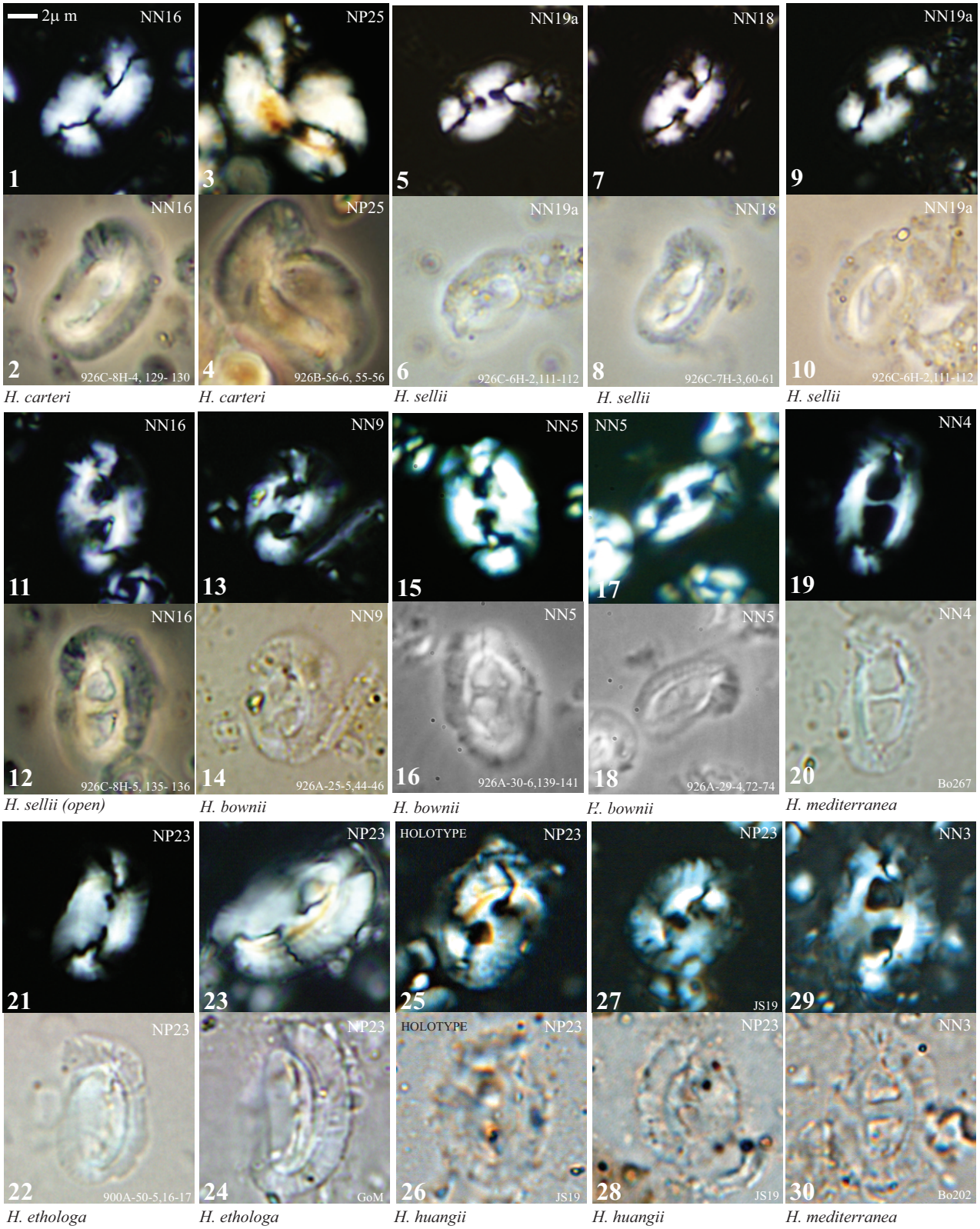

2µ m
NN16
1
NP25
3
NN19a
5
NN18
7
NN19a
9
NN16
2
926C-8H-4, 129- 130
NP25
4
926B-56-6, 55-56
NN19a
6
926C-6H-2,111-112
NN18
8
926C-7H-3,60-61
NN19a
10
926C-6H-2,111-112
H. carteri
H. carteri
H. sellii
H. sellii
H. sellii
NN16
11
NN9
13
NN5
15
NN5
17
NN4
19
NN16
12
926C-8H-5, 135- 136
NN9
14
926A-25-5,44-46
NN5
16
926A-30-6,139-141
NN5
18
926A-29-4,72-74
NN4
20
Bo267
H. sellii (open)
H. bownii
H. bownii
H. bownii
H. mediterranea
NP23
21
NP23
23
HOLOTYPE
NP23
25
NP23
27
JS19
NN3
29
NP23
22
900A-50-5,16-17
NP23
24
GoM
HOLOTYPE
NP23
26
JS19
NP23
28
JS19
NN3
30
Bo202
H. ethologa
H. ethologa
H. huangii
H. huangii
H. mediterranea

Plate 2

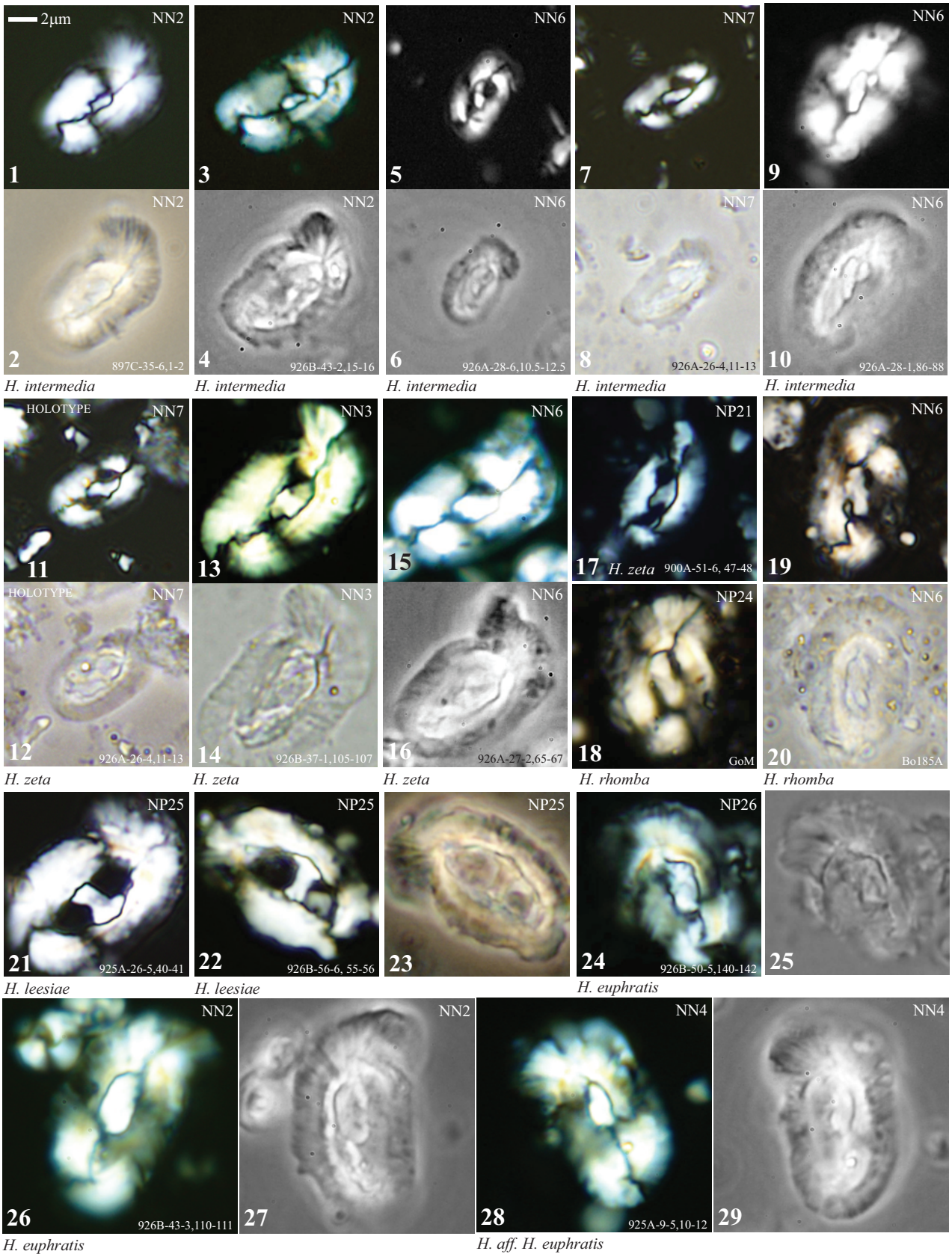

2µm
NN2
1
NN2
3
NN6
5
NN7
7
NN6
9
NN2
2
897C-35-6,1-2
NN2
4
926B-43-2,15-16
NN6
6
926A-28-6,10.5-12.5
NN7
8
926A-26-4,11-13
NN6
10
926A-28-1,86-88
H. intermedia
H. intermedia
H. intermedia
H. intermedia
H. intermedia
HOLOTYPE
NN7
11
NN3
13
NN6
15
NP21
17 H. zeta 900A-51-6, 47-48
NN6
19
HOLOTYPE
NN7
12
926A-26-4,11-13
NN3
14
926B-37-1,105-107
NN6
16
926A-27-2,65-67
NP24
18
GoM
NN6
20
Bo185A
H. zeta
H. zeta
H. zeta
H. rhomba
H. rhomba
NP25
21
925A-26-5,40-41
NP25
22
926B-56-6, 55-56
NP25
23
NP26
24
926B-50-5,140-142
25
H. leesiae
H. leesiae
H. euphratis
NN2
26
926B-43-3,110-111
NN2
27
NN4
28
925A-9-5,10-12
NN4
29
H. euphratis
H. aff. H. euphratis

Plate 3

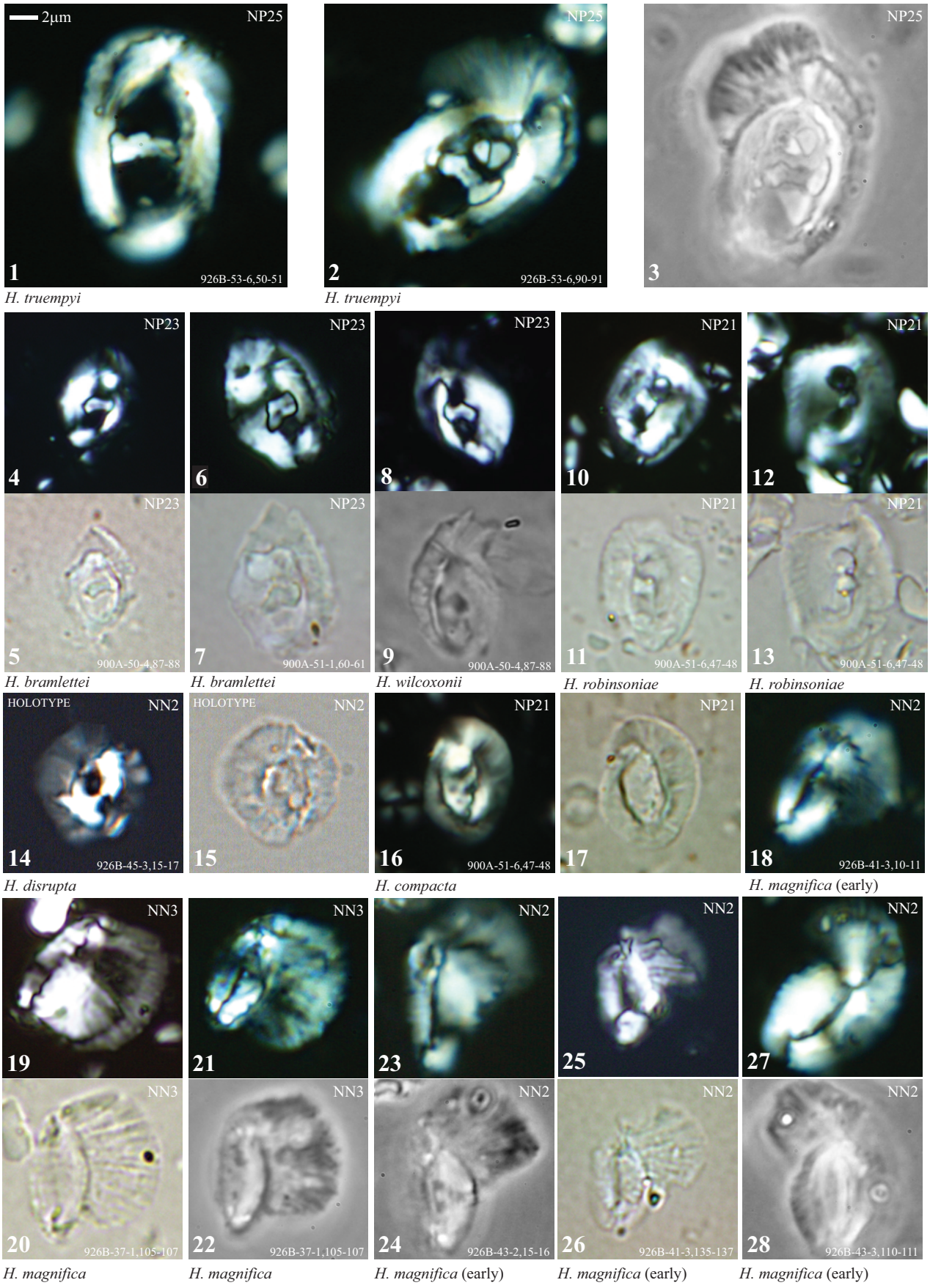
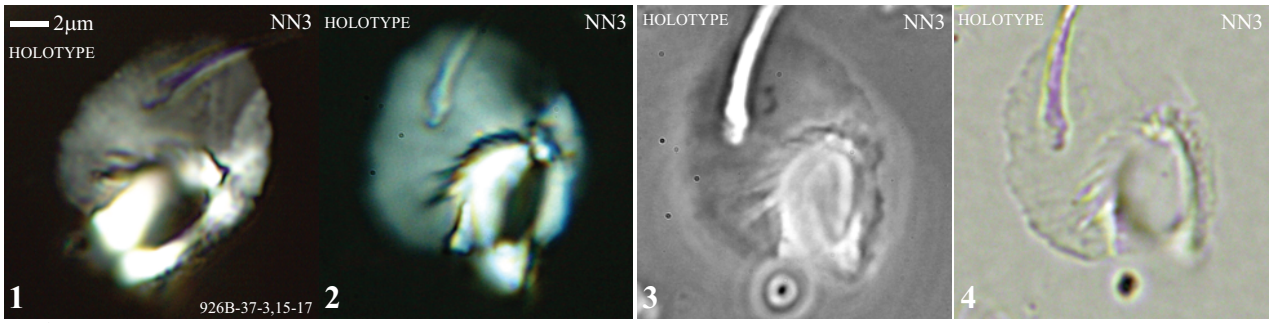
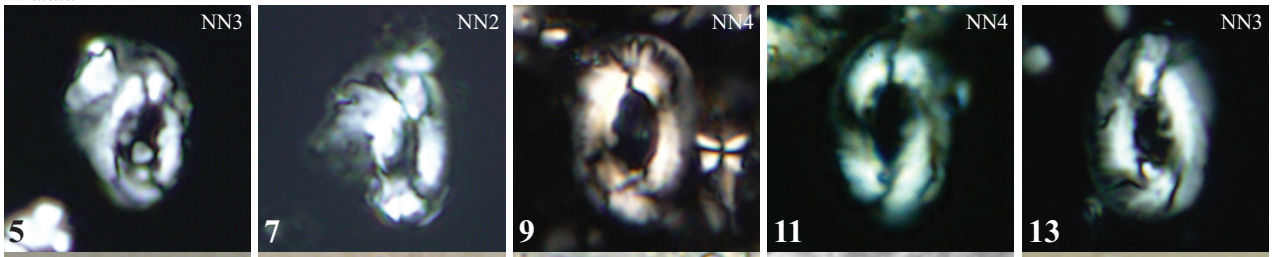

2µm
NP25
1
926B-53-6,50-51
H. truempyi
NP25
2
926B-53-6,90-91
H. truempyi
NP25
3
NP23
4
NP23
6
NP23
8
NP21
10
NP21
12
NP23
5
900A-50-4,87-88
H. bramlettei
NP23
7
900A-51-1,60-61
H. bramlettei
NP23
9
900A-50-4,87-88
H. wilcoxonii
NP21
11
900A-51-6,47-48
H. robinsoniae
NP21
13
900A-51-6,47-48
H. robinsoniae
HOLOTYPE
NN2
14
926B-45-3,15-17
H. disrupta
HOLOTYPE
NN2
15
NP21
16
900A-51-6,47-48
H. compacta
NP21
17
NN2
18
926B-41-3,10-11
H. magnifica (early)
NN3
19
NN3
21
NN2
23
NN2
25
NN2
27
NN3
20
926B-37-1,105-107
H. magnifica
NN3
22
926B-37-1,105-107
H. magnifica
NN2
24
926B-43-2,15-16
H. magnifica (early)
NN2
26
926B-41-3,135-137
H. magnifica (early)
NN2
28
926B-43-3,110-111
H. magnifica (early)

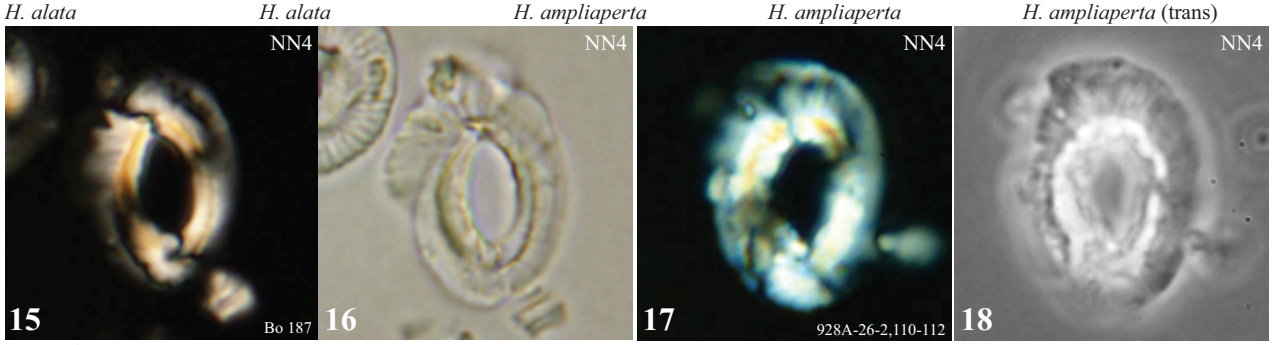
Plate 4



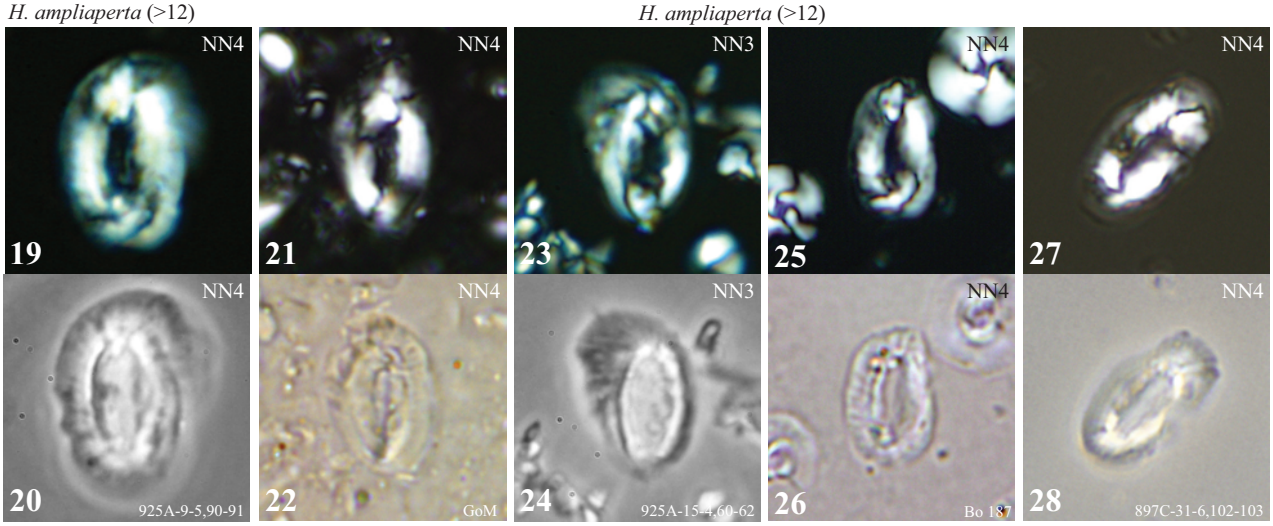
H. alata



H. alata *H. alata* *H. ampliaperta* *H. ampliaperta* *H. ampliaperta* (trans)

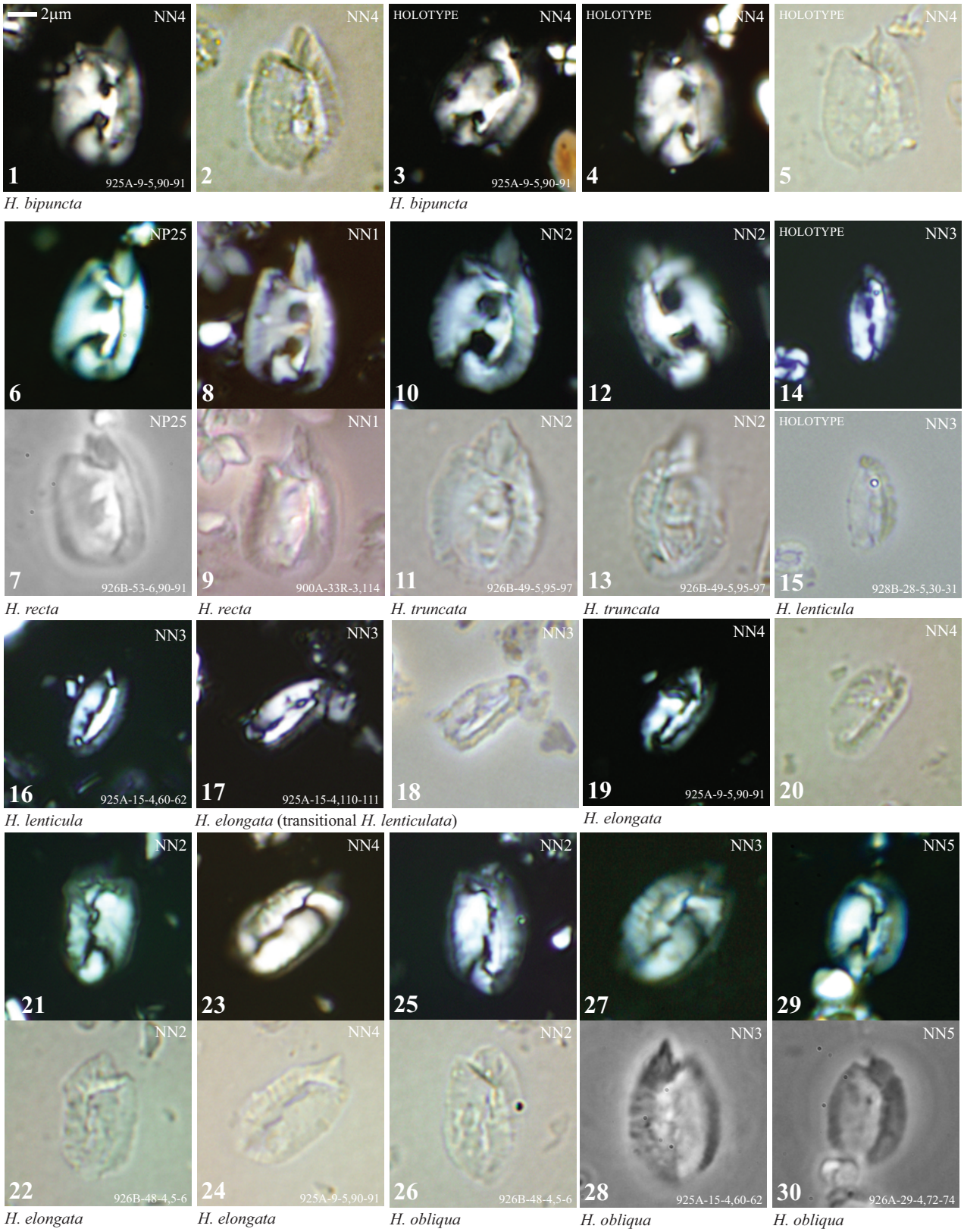


H. ampliaperta (>12) *H. ampliaperta* (>12)



H. scissura (trans) *H. scissura* *H. scissura* *H. scissura* *H. scissura*

Plate 5



H. bipuncta *H. bipuncta*

H. recta *H. recta* *H. truncata* *H. truncata* *H. lenticula*

H. lenticula *H. elongata* (transitional *H. lenticulata*) *H. elongata*

H. elongata *H. elongata* *H. obliqua* *H. obliqua* *H. obliqua*

Plate 6

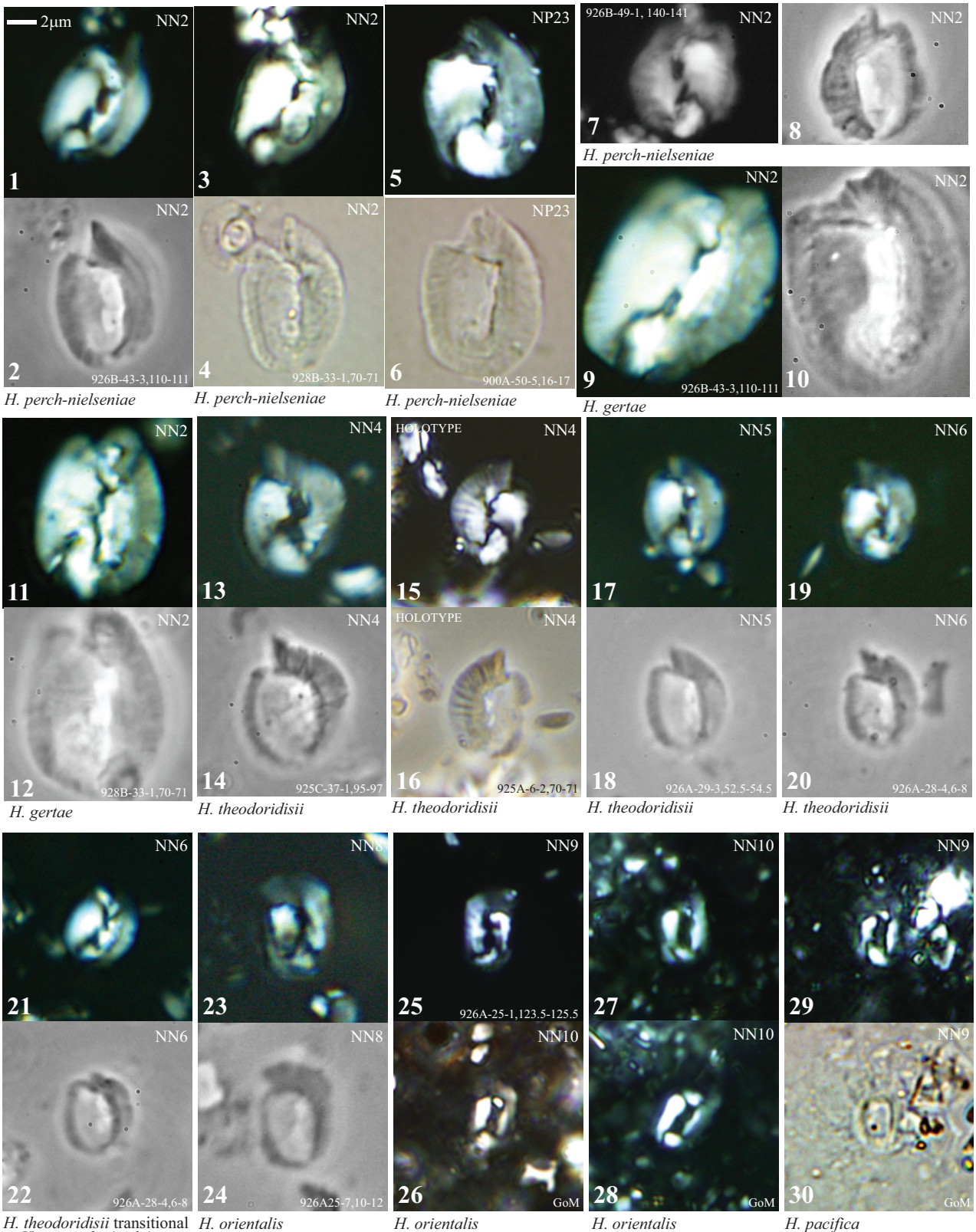

2µm
NN2
1
NN2
3
NP23
5
926B-49-1, 140-141
NN2
7
NN2
8
H. perch-nielseniae
NN2
2
926B-43-3,110-111
NN2
4
928B-33-1,70-71
NP23
6
900A-50-5,16-17
NN2
9
926B-43-3,110-111
NN2
10
H. perch-nielseniae
H. perch-nielseniae
H. perch-nielseniae
H. gertae
NN2
11
NN4
13
HOLOTYPE
NN4
15
NN5
17
NN6
19
NN2
12
928B-33-1,70-71
NN4
14
925C-37-1,95-97
HOLOTYPE
NN4
16
925A-6-2,70-71
NN5
18
926A-29-3,52.5-54.5
NN6
20
926A-28-4,6-8
H. gertae
H. theodoridisii
H. theodoridisii
H. theodoridisii
H. theodoridisii
NN6
21
NN8
23
NN9
25
926A-25-1,123.5-125.5
NN10
27
NN9
29
NN6
22
926A-28-4,6-8
NN8
24
926A25-7,10-12
NN10
26
GoM
NN10
28
GoM
NN9
30
GoM
H. theodoridisii transitional to H. orientalis (early)
H. orientalis
H. orientalis
H. orientalis
H. pacifica

Plate 7

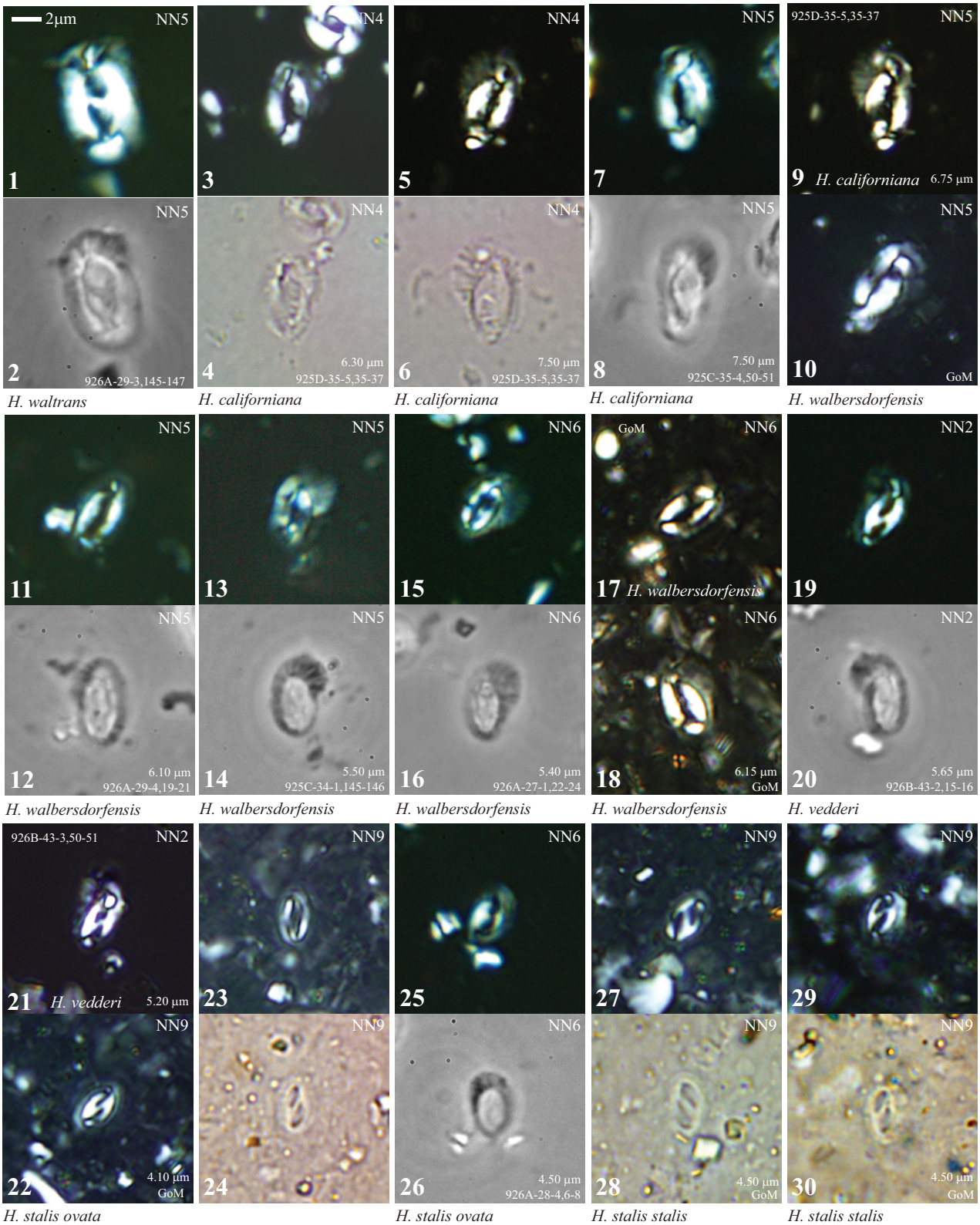
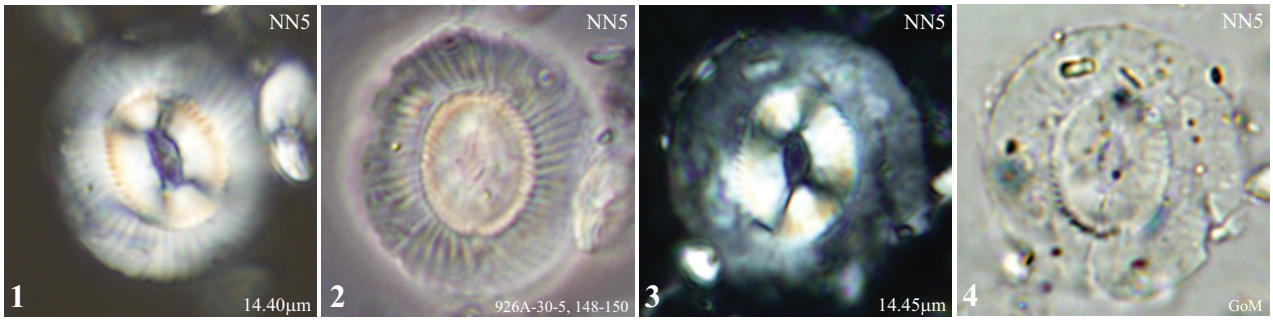
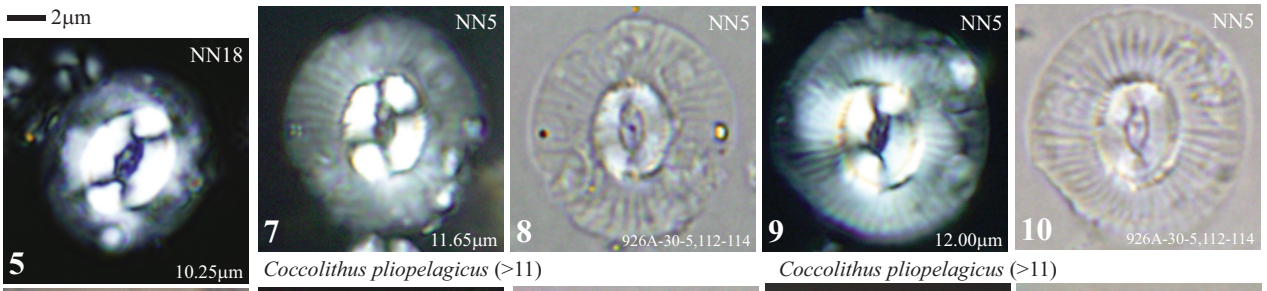

2µm
NN5
1
NN4
3
NN4
5
NN5
7
925D-35-5,35-37
NN5
9 H. californiana 6.75 µm
NN5
2
926A-29-3,145-147
NN4
4
6.30 µm
925D-35-5,35-37
NN4
6
7.50 µm
925D-35-5,35-37
NN5
8
7.50 µm
925C-35-4,50-51
NN5
10
GoM
H. waltrans
H. californiana
H. californiana
H. californiana
H. walbersdorfensis
NN5
11
NN5
13
NN6
15
GoM
NN6
17 H. walbersdorfensis
NN2
19
NN5
12
6.10 µm
926A-29-4,19-21
NN5
14
5.50 µm
925C-34-1,145-146
NN6
16
5.40 µm
926A-27-1,22-24
NN6
18
6.15 µm
GoM
NN2
20
5.65 µm
926B-43-2,15-16
H. walbersdorfensis
H. walbersdorfensis
H. walbersdorfensis
H. walbersdorfensis
H. vedderi
926B-43-3,50-51
NN2
21 H. vedderi 5.20 µm
NN9
23
NN6
25
NN9
27
NN9
29
NN9
22
4.10 µm
GoM
NN9
24
NN6
26
4.50 µm
926A-28-4,6-8
NN9
28
4.50 µm
GoM
NN9
30
4.50 µm
GoM
H. stalis ovata
H. stalis ovata
H. stalis stalis
H. stalis stalis

Plate 8

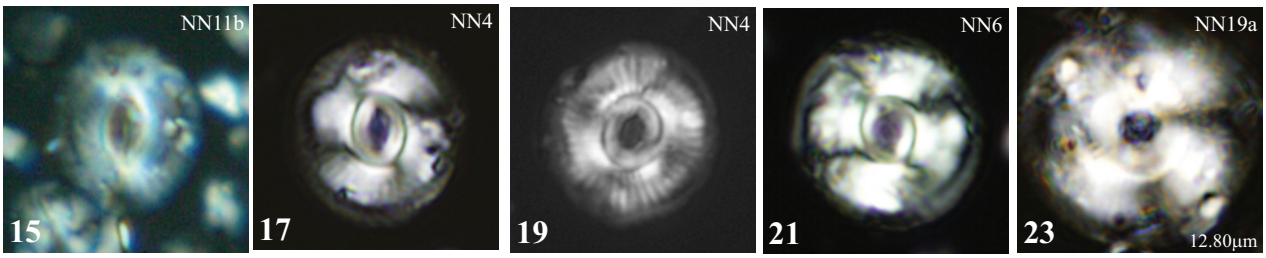


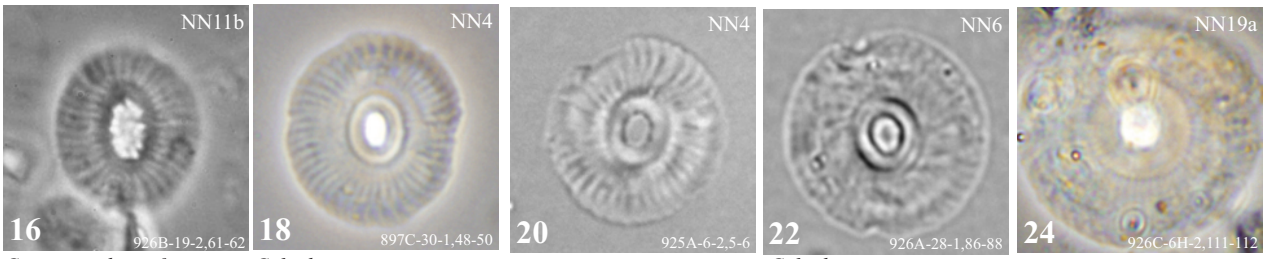
Coccolithus miopelagicus — *Coccolithus miopelagicus*



Coccolithus pliopelagicus (>11) — *Coccolithus pliopelagicus* (>11)

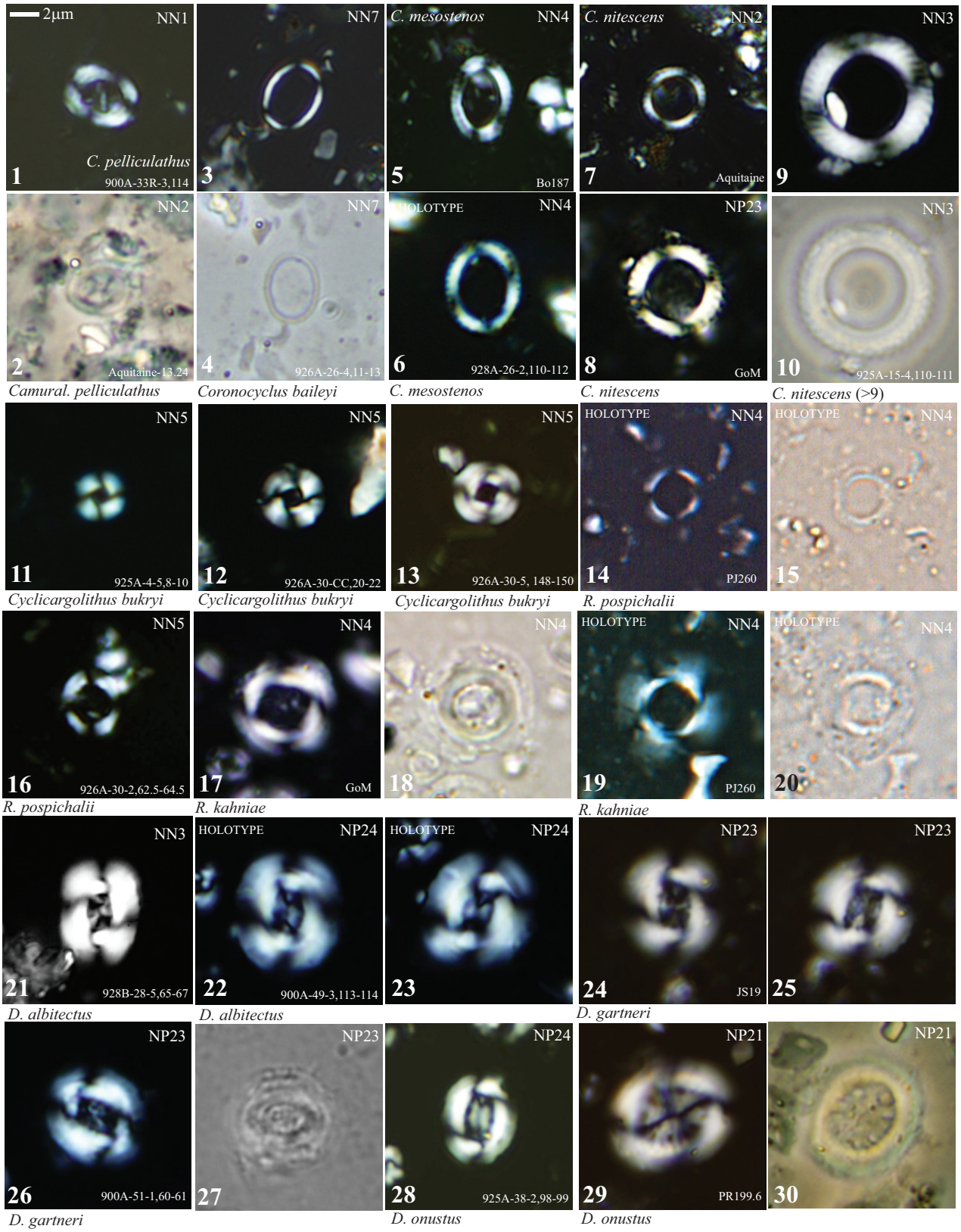
Coccolithus pelagicus — *Cryptococcolithus mediaperforatus* — *Cryptococcolithus mediaperforatus*





Crypto. mediaperforatus — *Calcidiscus premacintyrei* — *Calcidiscus premacintyrei* — *Calcidiscus premacintyrei* — *Calcidiscus macintyrei*

Plate 9


2µm
NN1
C. pelliculathus
900A-33R-3,114
1
NN7
3
C. mesostenos
NN4
Bo187
5
C. nitescens
NN2
Aquitaine
7
NN3
9
NN2
Aquitaine-13.24
2
Camural. pelliculathus
NN7
926A-26-4,11-13
4
Coronocyclus baileyi
HOLOTYPE
NN4
928A-26-2,110-112
6
C. mesostenos
NP23
GoM
8
C. nitescens
NN3
925A-15-4,110-111
10
C. nitescens (>9)
NN5
925A-4-5,8-10
11
Cyclicargolithus bukryi
NN5
926A-30-CC,20-22
12
Cyclicargolithus bukryi
NN5
926A-30-5, 148-150
13
Cyclicargolithus bukryi
HOLOTYPE
NN4
PJ260
14
R. pospichalii
HOLOTYPE
NN4
15
NN5
926A-30-2,62.5-64.5
16
R. pospichalii
NN4
GoM
17
R. kahniae
NN4
18
HOLOTYPE
NN4
PJ260
19
R. kahniae
HOLOTYPE
NN4
20
NN3
928B-28-5,65-67
21
D. albitectus
HOLOTYPE
NP24
900A-49-3,113-114
22
D. albitectus
HOLOTYPE
NP24
23
NP23
JS19
24
D. gartneri
NP23
25
NP23
900A-51-1,60-61
26
D. gartneri
NP23
27
NP24
925A-38-2,98-99
28
D. onustus
NP21
PR199.6
29
D. onustus
NP21
30