

# Uppermost Oligocene to Middle Miocene *Discoaster* and *Catinaster* taxonomy and stratigraphy in the circum North Atlantic Basin: Gulf of Mexico and ODP Leg 154

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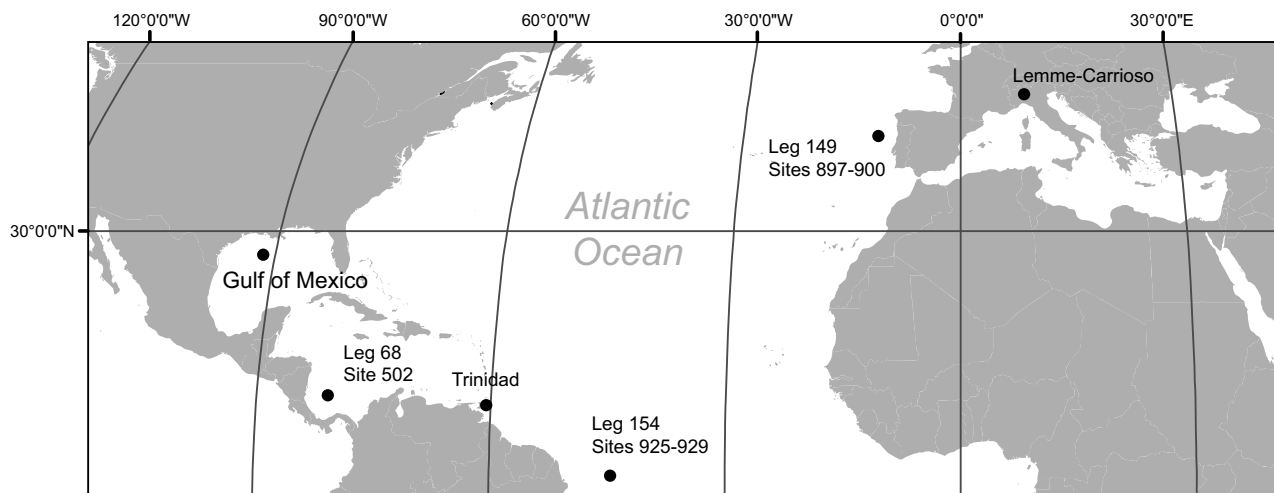
**Abstract** The genus *Discoaster* is of primary significance for Neogene nannofossil biostratigraphy in the Gulf of Mexico. The taxonomy and biostratigraphy of seven Lower to Middle Miocene *Discoaster* groups are discussed and illustrated in this paper. Detailed taxonomic descriptions are supported with drawings and light photomicrographs to clarify taxonomic concepts. The species, emendations, and new species presented detail the concepts and ages utilized by BP in the Gulf of Mexico. The stratigraphic occurrences of calcareous nannofossils for the Gulf of Mexico are calibrated to the astronomical chronometer of ODP Leg 154 in the western equatorial Atlantic. The base of the Neogene was investigated by sampling the Global Boundary Stratotype Section and Point from the Lemme-Carrosio section in northern Italy. A new Zone (NP26) is introduced for the terminal Oligocene, and Zone NN1 is emended so that the NP/NN zonal boundary is now tied to the Paleogene/Neogene boundary. Fifty main biostratigraphic events are presented for the Gulf of Mexico and ODP Leg 154 from 23.155Ma to 9.826Ma. Two new *Catinaster* species are described: *C. glenos* and *C. rotundus*. Eighteen new *Discoaster* species are described: *D. apetalus*, *D. arneyi*, *D. carneyi*, *D. catillomicros*, *D. catinatus*, *D. cuspidatus*, *D. discissus*, *D. durioi*, *D. emblematicus*, *D. gamberi*, *D. hexapleuros*, *D. leroi*, *D. patulus*, *D. premicros*, *D. salomonii*, *D. shumnykii*, *D. stellimicros*, and *D. ulnatus*. One new combination is introduced, *Discoaster virginianus*.

**Keywords** *Catinaster*, *Discoaster*, nannofossils, Oligocene, Miocene, Gulf of Mexico, GSSP, taxonomy, Leg 154, biostratigraphy

## 1. Introduction

The merger of BP with Amoco and Arco Vastar prompted the integration of the three heritage company Cenozoic biostratigraphic frameworks for the Gulf of Mexico (GoM) into a single BP framework. Subsequently, a twelve-year research program was initiated to calibrate the BP GoM framework to ODP Leg 154 (Figure 1) from the Cear  Rise in the western equatorial Atlantic. This research program also included work on the Oligocene-Miocene boundary Global Boundary Stratotype Section and Point (GSSP) in Italy (de Kaenel & Bergen, 2008; Bergen *et al.*, 2009; de Kaenel & Villa, 2010). These efforts yielded an astronomically-tuned Neogene time scale for the early Oligocene (30.679Ma) through early Pleistocene (1.595Ma) for the GoM and western equatorial Atlantic that has an average

biostratigraphic resolution of 141ky. To our knowledge, this is the only fully astronomically-tuned industrial time scale. The BP Gulf of Mexico Neogene Astronomically Tuned Time Scale (BP GNATTS) is currently in preparation for publication and contains the details of the age model, biostratigraphic horizon nomenclature, and event stratigraphy and calibration (Bergen *et al.*, in prep). The age model derived from Leg 154 is based on the astronomically-tuned cycles developed by Shackleton & Crowhurst (1997) and P like *et al.*, (2006) and was recalibrated to the orbital solution of Laskar *et al.*, (2004). High resolution sampling was employed with an average of 21ky, approximately equal to that of a precession cycle. A detailed description of the age model with methodology, sample depths, and ages will be presented in Bergen *et al.*, (in prep).



**Figure 1:** Map showing the locations of sample materials utilized and discussed in this study: the Ceará Rise (ODP Leg 154, Site 926), the Columbia Basin, western Caribbean Sea (DSDP Leg 68, Site 502), Trinidad, Galicia Margin (ODP Leg 149, Sites 897–900), Lemme-Carrioso (Italy) and the Gulf of Mexico

Extensive taxonomic discussions of BP species concepts and revisions of some Neogene species are provided in the five BP papers within this journal (Bergen *et al.*, 2017; Blair *et al.*, 2017; Browning *et al.*, 2017; Boesiger *et al.*, 2017; this paper) and must precede publication of the BP Neogene biostratigraphic chart (BP GNATTS; Bergen *et al.*, in prep). The taxonomy and biostratigraphy of the genus *Catinaster* and the Upper Oligocene to lower Middle Miocene *Discoaster* are the focus of this paper. The utility of these groups in Upper Oligocene to lower Upper Miocene GoM sediments is greatly expanded, including the calibration of 50 main biostratigraphic events and the description of 20 new taxa.

## 2. Material and methods

The materials used for this study are from outcrops, core, and well cuttings (Figure 1). Most of these were collected from ODP cores of Leg 154 at the IODP repository in Bremen (Germany). ODP Leg 154 is situated on the Ceará Rise in the western tropical Atlantic. Other DSDP/ODP samples are from Leg 68, Hole 502 (Columbia Basin, Western Caribbean Sea) and Leg 149, Holes 897C, 898A, 899A, 899B and 900A (northeast Atlantic Ocean). Additional samples were examined from the Bolli collection sampled by H.M. Bolli in 1957 in Trinidad (Bolli, 1957), deep-water GoM well materials (predominantly ditch-cutting samples), and sections from the historical stratotype of the Aquitanian stage (Aquitaine, Southwest France). Specimens illustrated herein were recovered from five Trinidad samples: (1) Bo267, *Catapsydrax dissimilis* Zone, Zone NN2; (2) PJ260, *Globorotalia fohsi fohsi* Zone, Zone NN4; (3) JS32, *Globorotalia fohsi lobata* Zone, Zone NN6; (4) Bo355, *Globorotalia fohsi robusta* Zone, Zone NN7; and (5) KR23422, *Globorotalia menardi* Zone, Zone NN9.

The low-latitude composite section from ODP Leg 154 was sampled at an average resolution of 21ky from

the Lower Oligocene (30.679Ma) to the Lower Pleistocene (1.595Ma); a total of 1366 samples were examined. Thirty-nine samples collected from the Lemme-Carrioso section in northern Italy, the base of Neogene GSSP, were examined to help resolve nannofossil boundary criteria for upper Zone NP25 to basal Zone NN2. The following stratigraphic abbreviations are used: LO (lowest occurrence) and HO (highest occurrence); abundance modifiers are: R (regular or persistent) for LRO and HRO, F (few) for LFO and HFO, C (common) for LCO and HCO, A (abundant) for LAO and HAO, and Acme.

The objective of this work is to clarify taxonomic concepts and present the GoM stratigraphy developed over the past five decades within 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 through the manuscript for consistency. Errors presented for ages are the difference in age for the next sample analyzed upwards or downwards in the composite section.

## 3. Biostratigraphy

Historically, industrial schemes use tops (HO) and assemblage changes as criteria; however, fossil bases (LO) are now routinely utilized in modern GoM wells because downhole caving is rarely problematic. The use of fossil bases not only enhances biostratigraphic resolution and interpretations in wells, but makes possible direct calibration to published schemes in their entirety. Calibration to published Cenozoic nannofossil zonations (Martini, 1971; Okada & Bukry, 1980) is effective because of their global reach, long term use and communication of results. The Cenozoic zonation of Martini (1971) is our main reference for the GoM. The GoM heritage schemes have long

indicated problems with the application of the Martini (1971) zonation around the Paleogene-Neogene boundary (Zones NP 25 and NN1), both in terms of the sequence of events and calibration to the boundary. This issue can now be resolved with the addition of internal research on the ratified base Neogene reference section in northern Italy (GSSP) and the astronomical chronometer of ODP Leg 154. The BP GNATTS is based on calcareous nannofossils and foraminifera; a full description of this zonation will be provided Bergen *et al.*, (in prep).

The top of the *Sphenolithus ciperoensis* Zone (NP25) of Martini (1970; 1971) was originally defined on the HO of *Helicosphaera recta* by Bramlette & Wilcoxon (1967a). BP has long recognized the HO of both *H. truncata* and *H. recta* (other authors consider *H. truncata* a junior synonym of *H. recta*) within Zone NN2 in the GoM, and now Leg 154, where they are dated at 21.041Ma and 20.170Ma, respectively (Boesiger *et al.*, 2017; this volume). Martini (1986) proposed another event as a substitute, the HO of *Zygrhablithus bijugatus*, which we have observed to range far up into the Lower Miocene. Bukry & Bramlette (1970) used the extinctions of both *S. ciperoensis* and *Dictyococcites bisectus* to mark the top of the *S. ciperoensis* Zone. Both of these events were later adopted by Bukry (1973a/b, 1975) to mark the top of his *S. ciperoensis* Zone, later coded as Zone CP19 in Okada & Bukry (1980). The extinction of *S. ciperoensis*, which represents the end of a lineage, is dated at 24.215Ma (Bergen *et al.*, 2017; this volume) and falls 1.185Ma below the base of the Neogene. *Dictyococcites bisectus* is problematic in that the species may or may not be distinguished from the larger *D. stavensis*. Furthermore, *D. bisectus* ranges up into the Lower Miocene in both the GoM and Leg 154, dated in the latter at 19.011Ma (926B-38X-5, 135–137cm; error 0.020Ma).

We propose a new zone (NP26) to be placed between the top of Zone NP25 and the base of Zone NN1. Okada & Bukry (1980) showed an informal Zone NP26 in their Table II (between Zones NP25 and NN1), corresponding to their *Cyclicargolithus abisectus* Subzone (CN1a). The base of Subzone CN1a is defined by the HO of both *Sphenolithus ciperoensis* and *Dictyococcites bisectus* and the top by the end acme of *Cyclicargolithus abisectus*. The *C. abisectus* acme is placed 0.804 million years below the base of the Neogene in Leg 154 at 23.834Ma (Sample 926B-52X-5, 110–111cm; error 0.020Ma). Our new *Clausicoccus fenestratus* Zone (NP26) utilizes a proven Oligocene marker (HO of *S. ciperoensis*) and a solution which calibrates the NP26/NN1 zonal boundary to the base of the Neogene.

#### NP26 – *Clausicoccus fenestratus* Zone

Definition: Interval from the HO of *Sphenolithus ciperoensis* to LO of *Discoaster druggii* (10µm to <15µm)

Authors: de Kaenel & Bergen, this paper

Reference locality: Ocean Drilling Project Leg 154

Remarks: The HO of *S. ciperoensis* is placed in Sample 926B-53X-5, 70–71cm, dated at 24.215Ma (error 0.022Ma). The LO of medium-sized *Discoaster druggii* (10 to <15µm) is dated at 23.030Ma in the Leg 154 research (Table 1).

Discussion: Steininger *et al.*, (1997) placed the base of the Neogene at 35 meters (GSSP) in the Lemme-Carrosio reference section, but we were unable to locate the LO of *Discoaster druggii* (10 to <15µm) in that section. The HO of *S. ciperoensis* was placed at 60.0 meters in the Lemme-Carrosio section.

#### NN1 – *Triquetrorhabdulus carinatus* Zone - emended

Definition: Interval from the LO of *Discoaster druggii* (10µm to <15µm) to LO of *Discoaster druggii* (≥15µm)

Authors: Bramlette & Wilcoxon (1967a), emended de Kaenel & Bergen, this paper

Reference locality: Ocean Drilling Program Leg 154

Remarks: In the Leg 154 research, the LO of medium-sized *Discoaster druggii* (10 to <15µm) is dated at 23.030Ma, and the LO of large of *D. druggii* (≥15µm) is dated at 22.757Ma (Table 1). The HO of *Sphenolithus capricornutus* serves as a proxy for the base of the Neogene in an operational sense, being dated at 22.998Ma in the Leg 154 research (Bergen *et al.*, 2017; this volume).

Discussion: The LO of *Discoaster druggii* is the original marker for the base of Zone NN2 (Martini & Worsley, 1970; Martini, 1971). We have separated this species into three size categories, which have proven stratigraphic utility. Regarding their originations, these events (Table 1) are the:

- (1) LO of small *D. druggii* (<10µm) in the terminal Oligocene at 23.155Ma;
- (2) LO of medium *D. druggii* (10 to <15µm) at the base Neogene at 23.030Ma; and
- (3) LO of large *D. druggii* (≥15µm) is recorded at 22.757Ma.

The holotype of this species is 18.50µm. Utilization of the large morphotype (≥15µm) to mark the base of Zone NN2 conforms to the original definition of the species, whereas the origin of the medium-sized *D. druggii* marries the base of Zone NN1 to the base of the Neogene.

## 4. Systematic palaeontology

In Oligocene to Pliocene sediments, six-rayed variants of *Discoaster* are the dominant (i.e., more diverse and abundant) forms. A notable exception is seen in the Late Miocene when five-rayed taxa of the *D. quinqueramus* and *D. prepentaradiatus* groups were common. In many of the *Discoaster* groups, distinct forms can be differentiated by the number of rays, which can vary from three to seven, and by whether or not the asterolith is symmetric or asymmetric. Many of these forms have different stratigraphic ranges, making their taxonomic separation useful. Browning *et al.*, (this volume) and Blair *et al.*, (this volume) detail these variations in ray number and form in Late Miocene to Pliocene species of *Discoaster*.

Taxon	Event	Zone Martini 71	Age (Ma)	Error, (Ma)	Hole-Core-Sec. cm-cm	Depth (rmcd) <sub>2</sub>
<i>C. coalitus</i>	HO/HRO	NN9	9.826	0.023	926A-24H-3, 60–62cm	241.21
<i>D. micros</i>	HO	NN9	10.082	0.017	926A-24H-5, 107–109cm	244.68
<i>C. coalitus</i> (>10µm)	HO	NN9	10.403	0.024	926A-25H-1, 35–37cm	248.71
<i>C. coalitus</i>	INC	NN9	10.403	0.024	926A-25H-1, 35–37cm	248.71
<i>C. coalitus</i>	LFO/LCO	NN9	10.732	0.020	926A-25H-3, 67–69cm	252.03
<i>D. emblematicus</i>	HO	NN8	11.037	0.011	926A-25H-5, 131–133cm	255.67
<i>D. cuspidatus</i>	HO	NN8	11.037	0.011	926A-25H-5, 131–133cm	255.67
<i>D. ulnatus</i>	HO	NN8	11.037	0.011	926A-25H-5, 131–133cm	255.67
<i>D. hexapleuros</i> (knob)	HO	NN8	11.155	0.022	926A-25H-6, 103–105cm	256.89
<i>D. patulus</i>	HO	NN8	11.509	0.019	926A-26H-2, 26.5–28.5cm	262.14
<i>D. kugleri</i>	HO/HRO	NN8	11.509	0.019	926A-26H-2, 26.5–28.5cm	262.14
<i>D. hexapleuros</i>	HO	NN8	11.531	0.004	926A-26H-2, 51.8–53.8cm	262.39
<i>C. coalitus</i>	LO	<b>base NN8</b>	11.531	0.011	926A-26H-2, 51.8–53.8cm	262.39
<i>D. deflandrei</i>	HO/HRO	NN7	11.575	0.033	926A-26H-2, 108–110cm	262.95
<i>D. kugleri</i>	HCO	NN7	11.575	0.033	926A-26H-2, 108–110cm	262.95
<i>D. kugleri</i>	acme	NN7	11.625	0.036	926A-26H-2, 141.5–143.5cm	263.29
<i>D. kugleri</i>	LCO	NN7	11.760	0.015	926A-26H-3, 141–143cm	264.78
<i>D. sanmiguelensis</i>	HO	NN7	11.849	0.023	926A-26H-4, 112–114cm	265.99
<i>D. kugleri</i>	LO	<b>base NN7</b>	11.910	0.005	926A-26H-5, 55–57cm	266.92
<i>D. hexapleuros</i>	LO	NN6	11.962	0.025	926A-26H-6, 12.5–14.5cm	268.00
<i>D. sanmiguelensis</i>	HRO	NN6	12.173	0.019	926A-27H-1, 131–133cm	271.53
<i>D. hexapleuros</i> (knob)	LO	NN6	12.186	0.018	926A-27H-2, 15.5–17.5cm	271.88
<i>D. cuspidatus</i>	LRO	NN6	12.968	0.021	926A-28H-3, 57.5–59.5cm	283.78
<i>D. cuspidatus</i>	LO	NN6	13.027	0.021	926A-28H-4, 26–28cm	284.96
<i>D. musicus</i>	HO	NN6	13.067	0.019	926A-28H-4, 107.5–109.5cm	285.78
<i>D. cuspidatus</i> (knob)	LO	NN6	13.217	0.023	926A-28H-6, 10.5–12.5cm	287.81
<i>D. petaliformis</i>	HO	NN5	13.637	0.024	926A-29H-5, 125–127cm	296.95
<i>D. druggii</i> (<10)	HO	NN5	13.856	0.023	926A-30H-1, 37–39cm	300.48
<i>D. arneyi</i>	HO	NN5	14.091	0.011	926A-30H-4, 51–53cm	305.12
<i>D. premicros</i>	HO	NN5	14.189	0.009	926A-30H-5, 59.5–61.5cm	306.71
<i>D. deflandrei</i>	INC	NN5	14.320	0.004	926A-30-CC, 5–7cm	309.82
<i>D. druggii</i> (10<15)	HO	NN5	14.320	0.004	926A-30-CC, 5–7cm	309.82
<i>D. premicros</i>	HRO	NN5	14.397	0.019	925A-4X-5, 49–50cm	358.54
<i>D. musicus</i>	LO	NN5	14.497	0.020	925C-35X-2, 30–31cm	364.98
<i>D. premicros</i>	INC	NN5	14.539	0.022	925C-35X-2, 115–117cm	365.84
<i>D. petaliformis</i>	acme	NN5	14.617	0.018	925C-35X-3, 120–122cm	367.38
<i>D. salomonii</i>	HO	NN4	15.098	0.019	925D-35H-6, 50–52cm	371.69
<i>D. leroyi</i>	HRO	NN4	15.379	0.022	925C-37X-2, 40–41cm	385.63
<i>D. premicros</i>	LO	NN4	15.498	0.021	925C-37X-4, 30–32cm	388.54
<i>D. petaliformis</i>	LO	NN4	15.778	0.019	925D-37H-4, 40–41cm	397.79
<i>D. arneyi</i>	LO	NN4	15.857	0.019	925C-38X-2, 90–91cm	404.34
<i>D. deflandrei</i>	HCO	NN4	16.537	0.020	925A-9H-6, 20–22cm	408.05
<i>D. shumnykii</i>	HRO	NN4	17.258	0.020	928B-27X-5, 70–71cm	269.64
<i>D. deflandrei</i>	HAO	NN4	17.456	0.031	928B-28X-2, 15–16cm	274.29
<i>D. druggii</i> (≥15)	HRO	NN4	17.609	0.022	928B-28X-3, 145–146cm	277.09
<i>D. calcosus</i>	HO	NN3	18.132	0.020	926C-36X-1, 75–77cm	356.75
<i>D. saundersii</i>	HO	NN3	18.852	0.020	926B-38X-3, 15–17cm	378.67
<i>D. druggii</i> (≥15)	LO	<b>base NN2</b>	22.757	0.020	928B-36X-6, 100–102cm	358.24
<i>D. druggii</i> (10<15)	LO	<b>base NN1</b>	23.030	0.008	926B-50X-5, 23–24cm	497.44
<i>D. druggii</i> (<10)	LO	NP26	23.155	0.018	929A-35X-3, 125–127cm	340.07

**Table 1:** Main events for the discussed *Discoaster* and *Catinaster* groups as observed in Leg 154 and Gulf of Mexico. <sub>1</sub>error in age of next sample. <sub>2</sub>revised meters composite depth



Late Oligocene to Middle Miocene *Discoaster* species are discussed herein, and 18 new species are introduced. The genus *Catinaster* is also considered, with the introduction of two new species. *Catinaster virginianus* Self-Trail (2014) is transferred to the genus *Discoaster*. Seven groups of *Discoaster* and the genus *Catinaster* have been systematized according to their morphologic similarities, each group named after a representative species. The *D. druggii* and *D. kugleri* groups have featureless central areas and simple ray terminations. These two groups are iterative and are best separated by geologic age. The *D. deflandrei* group has complex “wrenched” bifurcations and includes forms with both ornate and featureless central areas. The *D. sanmiguelensis* group has small, clubbed terminations and ornate central areas. *Discoaster musicus* shares this morphology but is distinguished by its large, stellate knob that extends to the central area periphery. Therefore, this distinct feature allows recognition of a separate grouping and remains diagnostic of the entire *D. musicus* group, which have variable ray morphologies. Species with flat ray terminations with variable central area morphologies are characteristic of the *D. micros* group. The *D. petaliformis* group consists largely of six-rayed asteroliths with high stems and/or bifurcate ray terminations.

Morphologic terminology follows the guidelines of Young *et al.*, (1997). The distal face is the convex side with sutural ridges. The proximal face is the concave side. A knob is a rounded, central structure usually located on the proximal side. A stem is a stellate, central structure on the distal or proximal side. The following size categories are utilized in this study: *very small* (<5 $\mu$ m); *small* (5 to <10 $\mu$ m), *medium* (10 to <15 $\mu$ m); *large* (15 to <20 $\mu$ m); *very large* ( $\geq$ 20 $\mu$ m).

#### 4.1 *Discoaster druggii* group

This group has featureless central areas and tapered rays with simple terminations. These terminations may be rounded, notched or truncate. Lateral nodes may be present but are not diagnostic of species. The *D. kugleri* group shares these morphological features, but evolved during the Middle Miocene about 639ky after the extinction of the *D. druggii* group (Figure 2). Three species are considered in the *D. druggii* group, including the new species *D. shumnykii*.

##### Genus *Discoaster* Tan, 1927

##### *Discoaster druggii* Bramlette & Wilcoxon, 1967a

Pl. 1, figs 1–5, 7–10, 12–18

1967a *Discoaster extensus* Bramlette & Wilcoxon, p. 110, pl. 8, figs. 2–8

1967b *Discoaster druggii* Bramlette & Wilcoxon, p. 220, *nom. nov. pro Discoaster extensus* Bramlette & Wilcoxon 1967, *non Discoaster extensus* Hay 1967

**Remarks:** *Discoaster druggii* has a large central area and long rays. Bramlette & Wilcoxon (1967a) gave a size

range of 15–22 $\mu$ m for the species. The holotype (18.5 $\mu$ m) was recovered from the Burdigalian *Catapsydrax dissimilis* Zone (NN2), and this type sample material (Bo267) has been used in this study to illustrate additional specimens (Pl. 1; figs. 5, 10, 16–18). We have divided this species into three size categories separated at 10 and 15 $\mu$ m. *Discoaster shumnykii* differs from *D. druggii* by its short rays. The free ray length to central area ratio is greater than one-third for *D. druggii* (0.36–0.71 ratio), based on 22 measured specimens (Bramlette & Wilcoxon, 1967a; this paper).

**Occurrence:** The sequence of bases for the three size categories of *D. druggii* is well-established in Leg 154 (Table 1; Figure 2). Utilized as events in the GoM, their extinctions occur in reverse order and have been calibrated to ODP Leg 154 as follows: HO of large *D. druggii* ( $\geq$ 15 $\mu$ m) at 17.347Ma (928B-27-CC, 30–32cm; error 0.009Ma), HO medium *D. druggii* (10 to <15 $\mu$ m) at 14.320Ma, and the HO of small *D. druggii* (<10 $\mu$ m) at 13.856Ma (Table 1). The HRO of large *D. druggii* is a GoM marker dated at 17.609Ma, along with the HO of both the small and medium-sized morphotypes (Table 1).

##### *Discoaster shumnykii* de Kaenel & Bergen, sp. nov.

Pl. 1, figs 6, 11; Pl. 3, figs 1–5

**Derivation of name:** In honor of nannofossil biostratigrapher Anatoliy Shumnyk (Bugware Inc., Tallahassee, FL, USA)

**Description:** A small to medium-sized *Discoaster* with short, tapering free rays and slightly indented ray terminations. The free rays may have small lateral nodes. The inter-ray areas are rounded and shallow. The large central area is featureless and divided by linear sutures that extend to the center of the asterolith.

**Remarks:** *Discoaster shumnykii* has shorter rays than *D. druggii*. For *D. shumnykii*, the free ray length to central area ratio less than one-third (0.21–0.28 on six measured specimens). *Discoaster obtusus* is a thicker form with more pointed ray tips. *Discoaster shumnykii* may be ancestral to both *D. obtusus* and *D. druggii*. *Discoaster kugleri* is morphologically similar to *D. shumnykii*, but their stratigraphic ranges are separated by approximately 5.27My. *Discoaster shumnykii* has been referred to as “*D. druggii* (stubby)” in the BP GoM lexicon.

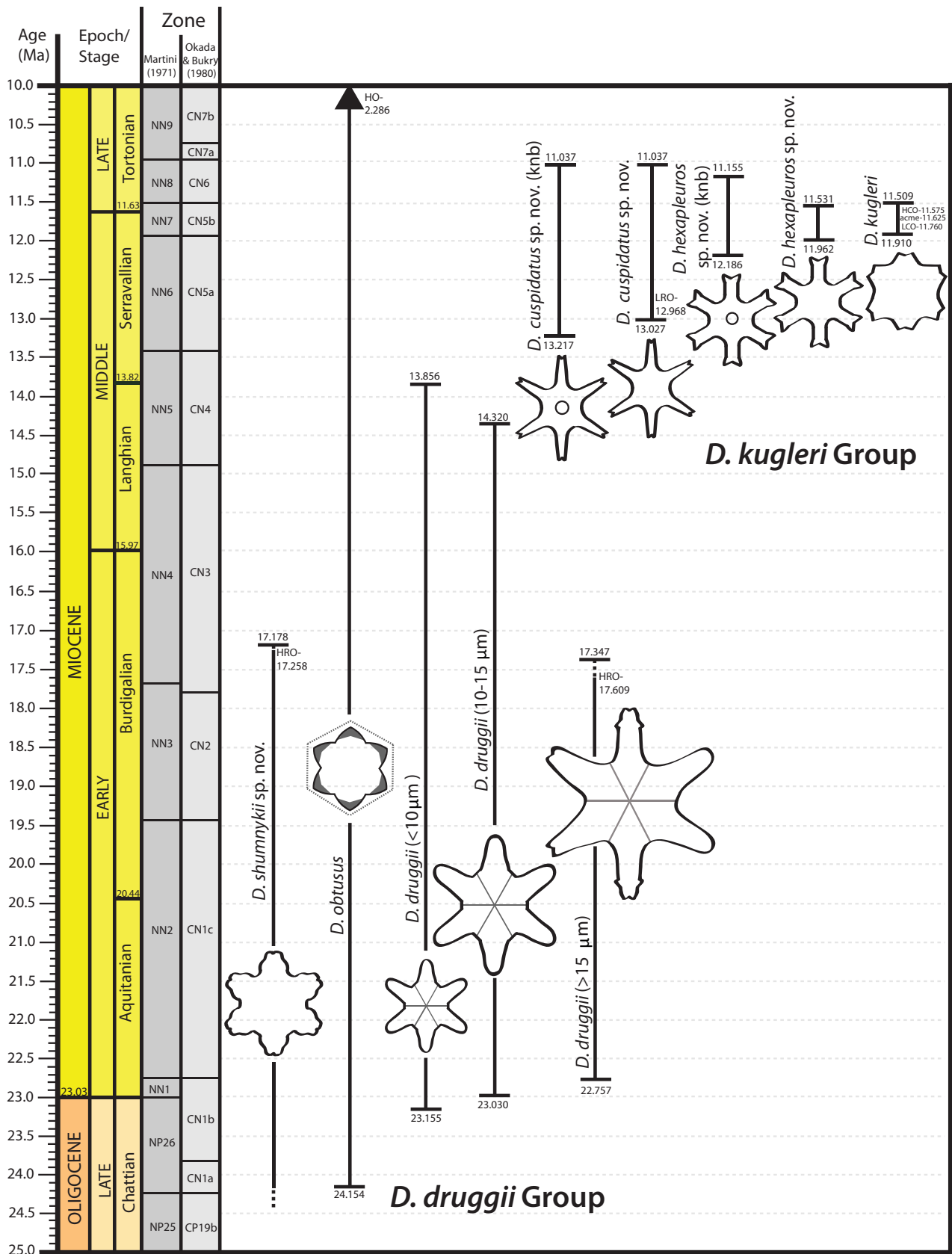
**Holotype dimension:** 9.4 $\mu$ m

**Holotype:** Pl. 3, figs 2–3

**Type locality:** South Trinidad, from Bolli (1957)

**Type level:** Sample Bo267, *Catapsydrax dissimilis* Zone, Cipero Formation, Zone NN2

**Occurrence:** *Discoaster shumnykii* ranges from Upper Oligocene (NP25) to Lower Miocene (NN4), dated at 17.178Ma (928B-27X-4, 55–56cm; error 0.021Ma) in the Leg 154 research. The HRO of *D. shumnykii* is a BP GoM marker dated at 17.258Ma in the Leg 154 research (Table 1, Figure 2).



**Figure 2:** Range diagram of the *Discoaster druggii* and *D. kugleri* groups. Ranges and new ages for the NN (Martini, 1971) and CN (Okada & Bukry, 1980) zonations are derived from calibrations in ODP Leg 154 core samples as well as the Gulf of Mexico

***Discoaster obtusus* Gartner, 1967**

Pl. 3, figs 6–8

1967 *Discoaster obtusus* Gartner, p. 2, pl. 3, figs. 1–4, 5a–b, 6a–b

**Remarks:** The holotype (10µm) was recovered from sample Bo267 (Bolli, 1957), which has been placed in Zone NN2. *Discoaster obtusus* has a hexagonal outline and very short, pointed rays. *Discoaster obtusus* is a thicker form with shorter and more pointed rays than *D. shumnykii*.

**Occurrence:** *Discoaster obtusus* ranges from Upper Oligocene (NP26) to Upper Pliocene (NN18) in the Leg 154 material where it is dated from 24.154Ma (926B-53X-4, 85–86cm; error 0.019Ma) to 2.286Ma (926C-7H-6, 114–116cm; error 0.024Ma). The range of this taxon is not yet established in the GoM.

**4.2 *Discoaster kugleri* group**

The *Discoaster kugleri* group is characterized by taxa with large, mostly featureless central areas and rays with simple terminations. The group is comprised of three species distinguished by ray length, ray morphology (tapered or parallel-sided) and stratigraphic ranges. The presence or absence of an indistinct central knob also has proven to have stratigraphic significance and is used within the species. Like *D. druggii*, ray terminations can be pointed, rounded, or truncate. Lateral nodes may also be present.

Martini & Bramlette (1963) illustrated three specimens of *D. kugleri*, each representing the three species maintained herein. Their holotype (pl. 102, fig. 11) has very short, tapered rays with slightly notched tips; such specimens are referred to herein as *D. kugleri*. Their second specimen (pl. 102, fig. 12) has parallel-sided arms resulting in angular inter-rays and is described herein as *D. hexapleuros*. Such forms with hexagonal central area peripheries reflect common usage in the GoM among the three heritage companies. The presence or absence of a distal knob on such hexagonal forms with parallel-sided rays also have stratigraphic utility. Specimens with long, tapered rays (their plate 102, fig. 13) are described herein as *D. cuspidatus* and represent both the origin and extinction of the group.

The entire *D. kugleri* group is illustrated on Plate 2 and the lineage on Figure 2. *Discoaster cuspidatus* and *D. hexapleuros* clearly predate *D. kugleri*, which marks the base of Zone NN7 (=CN5b). The *D. kugleri* group is a stratigraphically-significant group with 13 coeval events established among the three species and five morphotypes in the GoM and Leg 154 (Table 1).

***Discoaster kugleri* Martini & Bramlette, 1963**

Pl. 2, figs 1–10

1963 *Discoaster kugleri* Martini & Bramlette (*pro parte*), p. 853, pl. 102, fig. 11; *non* pl. 102, figs. 12–13

**Remarks:** The holotype of *D. kugleri* is 10.3µm with very short, tapering rays and slightly indented ray terminations. The central area is featureless (no knob) but with distinct

distal sutures. The ratio of free ray length to central area size is normally from less than one-third for *D. kugleri* (0.20–0.31 ratio), but no higher than 0.40 (Pl. 2, figs 6–7). Size = 8–15µm.

**Occurrence:** The LO of *D. kugleri* marks the base of Zone NN7 in the upper Middle Miocene and is dated at 11.910Ma (Table 1). The HO of *D. kugleri* was observed in uppermost NN7, dated at 11.509Ma (Table 1). The LCO and HCO of *D. kugleri*, as well as its acme, also have stratigraphic utility in Zone NN7 (Table 1).

***Discoaster hexapleuros* de Kaenel & Bergen, sp. nov.**

Pl. 2, figs 11–20

1963 *Discoaster kugleri* Martini & Bramlette (*pro parte*), p. 853, pl. 102, fig. 12; *non* pl. 102, figs. 11, 13

**Derivation of name:** From Greek *hexa*, meaning six and *pleuros*, meaning side

**Diagnosis:** A late Middle to early Late Miocene *Discoaster* species having a large featureless central area (a low relief knob may be present) and parallel-sided rays with a corresponding hexagonal central area periphery.

**Description:** A small to medium-sized *Discoaster* with a large hexagonal central area and parallel-sided rays. The distal face of the central area is flat, usually featureless. A low-relief knob may be present. On the proximal face of the central area, strong ridges run the length of the rays and may meet in the center of the asteroth. The ray terminations are normally indented (“notched”). Lateral nodes may be present. Ray length is variable, with free ray length to central area ratios around one-half (0.44–0.53 on five measured specimens). Size = 7–15µm.

**Remarks:** *Discoaster hexapleuros* is distinguished from *D. cuspidatus* by its parallel-sided rays. *Discoaster kugleri* has short to very short tapering rays. *Discoaster hexapleuros* has been referred to as “*D. kugleri*” in the GoM by all three heritage companies.

**Holotype dimension:** 10.0µm

**Holotype:** Pl. 2, figs 11–13

**Type locality:** South Trinidad, Bolli (1957)

**Type level:** Sample Bo355, *Globorotalia fohsi robusta* Zone, Cipero Formation, Zone NN7

**Occurrence:** The presence or absence of a central knob has demonstrated stratigraphic utility in both the GoM and Leg 154 research. The successive downhole HOs of *D. hexapleuros* (knob) and *D. hexapleuros* are long-standing BP GoM markers, dated at 11.155Ma and 11.531Ma in the Leg 154 research (Table 1). The LO of *D. hexapleuros* (knob) is dated at 12.186Ma and predates the LO of *D. hexapleuros* at 11.962Ma (Table 1). *Discoaster hexapleuros* (knob) has been referred to as “*D. cf. kugleri* (knob)” in the BP GoM lexicon.

***Discoaster cuspidatus* de Kaenel & Bergen, sp. nov.**

Pl. 2, figs 21–30

1963 *Discoaster kugleri* Martini & Bramlette (*pro parte*), p. 853, pl. 102, fig. 13; *non* pl. 102, figs. 11–12

**Derivation of name:** From Latin *cuspidatus*, meaning to make pointed

**Diagnosis:** A Middle to early Late Miocene *Discoaster* species having a featureless central area (a low relief knob may be present) and six long, tapering rays.

**Description:** A small to medium-sized *Discoaster* species with a large featureless central area and relatively long, tapering rays. The distal face of the central area is flat, usually featureless. A low-relief knob may be present. On the proximal face of the central area, strong ridges run the length of the rays and may meet at the center of the asterolith. The ray terminations may be rounded, pointed or indented. Lateral nodes may be present. The ratio of the free ray length to central area varies between 0.45–0.80 (8 measured specimens). Size = 8–15  $\mu\text{m}$ .

**Remarks:** Martini & Bramlette (1963) stated that “some specimens show a very small central knob and weak ridges extending along the rays to one side of the median line” (p. 853). We noted specimens with a low relief distal knob (Pl. 2, fig. 25) as *D. cuspidatus* (knob). *Discoaster cuspidatus* is distinguished from *D. kugleri* by its free ray length and from *D. hexapleuros* by its tapered rays. *Discoaster cuspidatus* has been referred to as “*D. cf. kugleri* (taper)” in the BP GoM lexicon.

**Holotype dimension:** 11.6  $\mu\text{m}$

**Holotype:** Pl. 2, figs 21–22

**Type locality:** South Trinidad, Bolli (1957)

**Type level:** Sample Bo355, *Globorotalia foehi robusta* Zone, Cipero Formation, Zone NN7

**Occurrence:** *Discoaster cuspidatus* ranges from the Middle Miocene to early Late Miocene, dated from 13.217Ma to 11.037Ma (Table 1, Figure 2). The HO of *D. cuspidatus* marks a prominent stratigraphic horizon in the GoM, together with the HO of *D. emblematicus* and HO of *D. ulnatus* (Table 1) The LRO of the *D. cuspidatus* has also been utilized in GoM wells and dated at 12.968Ma in the Leg 154 research (Table 1). We have determined the same extinction levels for morphotypes with and without central knobs in the Leg 154 research, whereas the appearance of specimens with central knobs predate the appearance those without central knobs by approximately 190ky (Table 1).

### 4.3 *Discoaster deflandrei* group

This group is characterized by their complex, “wrenched” bifurcations. Although it includes species with featureless central areas (Pl. 3, figs 9–22) exemplified by *D. deflandrei*, these “wrenched” bifurcations differentiate them from the *D. kugleri* and *D. druggii* groups. The *D. deflandrei* group also includes taxa with ornate central areas (Pl. 4, figs 1–10), as typified by *D. saundersii*. The *D. sanmiguelensis* and *D. musicus* groups also have ornate central areas, but with different ray terminations. Eight taxa are included in the *D. deflandrei* group (Figure 3), including four new species and nine GoM events (Table 1).

### *Discoaster leroyi* de Kaenel & Bergen, sp. nov.

Pl. 3, figs 9–10

**Derivation of name:** In honor of former BP geologist Andy Leroy (Houston, TX, USA)

**Diagnosis:** A five-rayed species of the *D. deflandrei* group with a featureless central area.

**Description:** This five-rayed asterolith has flared, symmetrically-arranged rays with broad, ‘wrench’-like bifurcations. The inter-ray areas are rounded, free rays are medium length, and the central area is featureless.

**Remarks:** *Discoaster leroyi* is distinguished from other members of the *D. deflandrei* group by having five rays and a featureless central area.

**Holotype dimension:** 9.2  $\mu\text{m}$

**Holotype:** Pl. 3, fig. 10

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

**Type level:** Sample 926A-29-5, 80–82cm (13.613Ma), Zone NN5

**Occurrence:** *Discoaster leroyi* ranges from the Lower Eocene (NP10) to the Middle Miocene (NN7), which is dated at 11.794Ma (Sample 926A-26H-4, 37–39cm; error 0.019Ma). The HRO of *D. leroyi* is a GoM marker, dated at 15.379Ma (Table 1).

### *Discoaster salomonii* de Kaenel & Bergen, sp. nov.

Pl. 3, figs 11–12, 17

1954 *Discoaster deflandrei* Bramlette & Riedel (*pro parte*), p. 399, text fig. 1c; *non* pl. 39, fig. 6, text figs. 1a, 1b

**Derivation of name:** In memory of nannofossil biostratigrapher Ralph Salomon and former Amoco colleague (Houston, TX, USA)

**Diagnosis:** A six-rayed *Discoaster* species having a featureless central area and broad, ‘wrench’-like bifurcate rays with circular inter-ray areas.

**Description:** A medium-sized asterolith with six, short rays that taper and then flare distally to form broad ‘wrench’-like bifurcations. The large central area is featureless, and the ray sutures are distinct. The ray length and morphology combine to form diagnostic circular inter-ray areas.

**Remarks:** *Discoaster salomonii* is equivalent to the concept of *D. calculosus* employed by Amoco in the GoM. As used by BP, *D. calculosus* is a larger form (15  $\mu\text{m}$ ) with much shorter free ray length, forming broad and shallow inter-ray areas.

**Holotype dimension:** 9.6  $\mu\text{m}$

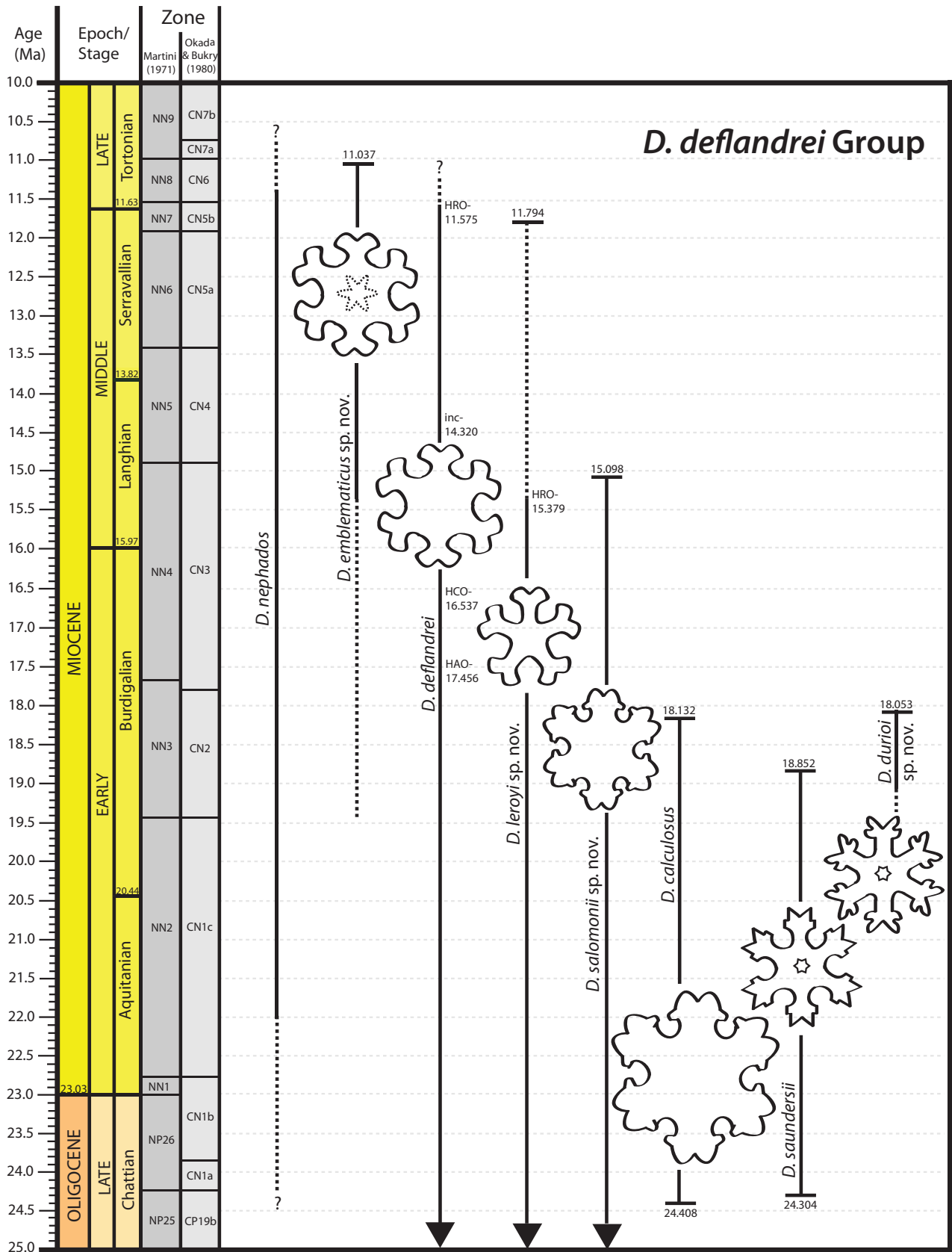
**Holotype:** Pl. 3, figs 11–12

**Type locality:** South Trinidad, Bolli (1957)

**Type level:** Sample Bo267, *Catapsydrax dissimilis* Zone, Cipero Formation, Zone NN2

**Occurrence:** Historically, the HO of *D. salomonii* has been used as GoM marker by Amoco and post-merger BP. This event has been dated in the Leg 154 research at 15.098Ma (Table 1). The species ranges into the Lower Oligocene.





**Figure 3:** Range diagram of the *Discoaster deflandrei* group. Ranges and new ages for the NN (Martini, 1971) and CN (Okada & Bukry, 1980) zonation are derived from calibrations in ODP Leg 154 core samples as well as the Gulf of Mexico

***Discoaster nephados* Hay, 1967**

Pl. 3, fig. 13

1967 *Discoaster nephados* Hay in Hay, Mohler, Roth, Schmidt & Boudreaux, p. 452, pl. 2, figs. 4–5**Remarks:** *Discoaster nephados* is a medium-sized *Discoaster* with short, flaring rays and very broad, wrench-like bifurcations; the central area is featureless. The space between bifurcations is very narrow, as the bifurcations almost touch.**Occurrence:** *Discoaster nephados* ranges from Upper Oligocene (upper NP25) to Upper Miocene (lower NN9).***Discoaster deflandrei* Bramlette & Riedel, 1954**

Pl. 3, figs 14–16

1954 *Discoaster deflandrei* Bramlette & Riedel (*pro parte*), p. 399, pl. 39, fig. 6, text fig. 1b; *non* text figs. 1a, 1c**Remarks:** *Discoaster deflandrei* is reserved for six-rayed specimens with flat, medium-sized central areas that are featureless. The rays flare and terminate in broad, ‘wrench’-like bifurcations. The inter-ray area is subcircular. Very rare specimens with three, four and seven rays are identified as variants of *D. deflandrei*. *Discoaster leroyi* is described herein for five-rayed *D. deflandrei* because of the demonstrated stratigraphic utility. *Discoaster emblematicus* is distinguished from *D. deflandrei* by its ornate central area.**Occurrence:** *Discoaster deflandrei* ranges from the Lower Eocene (NP10) to Upper Miocene. The HO is a long-standing BP marker in the GoM and dated at 11.575Ma on the HRO in the Leg 154 research (Table 1). Downhole increases in this species have been utilized as markers in the GoM by several workers; three such events have been calibrated to the BP scheme in the Leg 154 materials (Table 1).***Discoaster calculosus* Bukry, 1971**

Pl. 3, figs 18–22

1971 *Discoaster calculosus* Bukry, p. 46, pl. 2, figs. 7–9**Remarks:** This large *Discoaster* has broad and shallow inter-ray areas. The holotype of *D. calculosus* is 15µm. Bukry (1971) gave a size range of 11–21µm for the species. Its shallow inter-ray area distinguishes it from other members of the *D. deflandrei* group.**Occurrence:** *Discoaster calculosus* is a long-standing BP GoM marker and reserved for large specimens ( $\geq 15\mu\text{m}$ ). The HO is a GoM marker dated at 18.132Ma (Table 1). In Leg 154, the LO of the species is in Zone NP25 and dated at 24.408Ma (Sample 926B-54X-3, 30–31cm; error 0.048Ma).***Discoaster saundersii* Hay, 1967**

Pl. 4, figs 1–3

1967 *Discoaster saundersii* Hay in Hay, Mohler, Roth, Schmidt & Boudreaux, p. 453, pl. 3, figs. 2–6**Remarks:** *Discoaster saundersii* is a small to medium-sized *Discoaster* with a relatively small central area. Hay *et al.*, (1967) described the central disk as featureless; however, their illustrated specimens appear to have ornatecentral areas, and this concept has been maintained in the GoM for decades. *Discoaster saundersii* has the most idealized ‘wrenched’ bifurcations of the *D. deflandrei* group. The lower bifurcation pair is orthogonal to the ray orientation; the upper bifurcation pair roughly parallels the rays (i.e., perpendicular to the lower pair). The angular nature of its bifurcation pairs (i.e., orthogonal) distinguishes *D. saundersii* from both *D. durioi* and *D. emblematicus*.**Occurrence:** The HO of *D. saundersii* is a GoM marker in the Lower Miocene (lower NN3) and dated at 18.852Ma (Table 1). Hay *et al.*, (1967) reported the LO of *D. saundersii* in the Lower Oligocene (*Globigerina ampliapertura* Zone, NP23). We did not observe *D. saundersii* below the uppermost Oligocene (NP25) in Leg 154, placing the LO in Sample 926B-54X-1, 60–61cm (24.304Ma; error 0.022Ma).***Discoaster durioi* de Kaenel & Bergen, sp. nov.**

Pl. 4, figs 4–5

**Derivation of name:** In honor of GoM operations geologist Mark Durio (Houston, TX, USA)**Diagnosis:** A six-rayed *Discoaster* with broadly angular, ‘wrench’-like bifurcations and an ornate central area. The inner angle of the bifurcations is obtuse.**Description:** A medium-sized *Discoaster* species, normally with six rays that are short to medium length. Free ray length is roughly equal to the central area width. The bifurcations are broad and ‘wrench’-like (i.e., composed of paired elements). The lower bifurcation pair is orthogonal to the ray orientation. The upper bifurcation pair forms a low angle to the perpendicular of the ray orientation; its inner bifurcation angle is obtuse. The medium-sized central area has a prominent distal stellate stem surrounded by pitted depressions. The inter-ray areas are subcircular.**Remarks:** *Discoaster durioi* is distinguished from *D. saundersii* by the obtuse angle formed by the upper bifurcation pair. *Discoaster durioi* has been referred to as “*D. aff. saundersii*” in the BP GoM lexicon.**Holotype dimension:** 10.8µm**Holotype:** Pl. 4, fig. 4**Type locality:** South Trinidad, Bolli (1957)**Type level:** Sample Bo267, *Catapsydrax dissimilis* Zone, Cipero Formation, Zone NN2**Occurrence:** The HO of *D. durioi* has been associated with a stratigraphic horizon marked by the HRO of *S. belemnus* in six deep-water GoM wells. This stratigraphic horizon in upper Zone NN3 has been dated at 17.831Ma (Bergen *et al.*, 2017; this volume). *Discoaster durioi* was observed in samples from Zone NN3 in the Leg 154 research, where the HO is dated at 18.053Ma (Sample 926B-35X-6, 95–97cm; error 0.020Ma).***Discoaster emblematicus* de Kaenel & Bergen, sp. nov.**

Pl. 4, figs 6–10

**Derivation of name:** From Greek *emblema*, meaning ornament, inlaid work

**Diagnosis:** A six-rayed *Discoaster* with broadly rounded, ‘wrench’-like bifurcations and an ornate central area.

**Description:** A medium-sized *Discoaster* species normally with six rays that are short to medium length. Free ray length is generally less than the central area width. The bifurcations are broad and wrench-like (i.e., composed of paired elements). Both upper and lower bifurcation pairs form a low angle to the perpendicular of the ray orientation. The medium to large central area has a prominent stellate distal stem surrounded by pitted depressions, giving the species its ornate central character.

**Remarks:** *Discoaster emblematicus* is differentiated from *D. deflandrei* by its ornate central area. In both *D. saundersii* and *D. durioi*, the lower bifurcation pair is perpendicular to the ray orientation. *Discoaster emblematicus* has been referred to as “*D. deflandrei* (ornate)” in the BP GoM lexicon.

**Holotype dimension:** 10.0µm

**Holotype:** Pl. 4, fig. 6

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

**Type level:** Sample 926A-27-1, 131–133cm (12.173Ma), Zone NN6

**Occurrence:** The base of *D. emblematicus* has been observed in the GoM and Leg 154 within the Lower Miocene. The HO is a GoM marker within lowermost Upper Miocene (upper NN8) and dated at 11.037Ma (Table 1).

#### 4.4 *Discoaster sanmiguelensis* group

This group is distinguished morphologically by its narrow and rounded bifurcations (i.e. clubbed) and ornate central areas. The ornate central area contains both a large, distal, stellate stem surrounded by pitted depressions and a small proximal knob. The elements of the stellate stem project between the rays but do not reach near the central area periphery (unlike the *D. musicus* group).

The total range of the *D. sanmiguelensis* group, represented by *D. ulnatus*, is from upper Zone NN3 to upper Zone NN8. This extinction is coincident with the extinctions of both the *D. kugleri* group and “ornate” *D. deflandrei* group members and is dated at 11.037Ma. Three species are placed in the *D. sanmiguelensis* group including two new species, *D. patulus* and *D. ulnatus*. All three species were included within the original concept of *D. sanmiguelensis* by Bukry (1981), who illustrated 13 specimens. The appearance of *D. ulnatus* was followed shortly afterward by *D. patulus* and then by *D. sanmiguelensis*; their extinctions occurred in reverse order and are all deep-water GoM markers calibrated in the Leg 154 research (Table 1; Figure 4).

##### *Discoaster patulus* de Kaenel & Bergen, sp. nov.

Pl. 4, figs 11–14

1981 *Discoaster sanmiguelensis* Bukry (*pro parte*), p. 462, pl. 2, fig. 9; *non* pl. 2, figs. 7–8, 10; pl. 3, figs. 1–14

**Derivation of name:** From Latin *patulus*, meaning open, spread out

**Diagnosis:** A species of the *D. sanmiguelensis* group with rays that taper and then flare to form clubbed terminations.

**Description:** A small to medium-sized *Discoaster* species with a large ornate central area and relatively short rays. The free rays taper strongly and then flare to form narrow, thick bifurcations with rounded peripheries. The central area width is greater than the length of the free rays. A stellate, distal stem projects between the rays and does not reach the central area periphery; pitted depressions surround this stellate stem. Size = 8–13µm.

**Remarks:** *Discoaster sanmiguelensis* has parallel-sided rays and a hexagonal central area periphery, whereas *D. ulnatus* has longer, tapered rays. *Discoaster emblematicus* is distinguished from *D. patulus* by its broad (versus narrow) bifurcations. *Discoaster patulus* has been referred to as “*D. cf. sanmiguelensis*” in the BP GoM lexicon.

**Holotype dimension:** 9.6µm

**Holotype:** Pl. 4, figs 13–14

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

**Type level:** Sample 926A-27-4, 13.5–15.5cm (12.368Ma), Zone NN6

**Occurrence:** The HO of *D. patulus* marks the top of a GoM stratigraphic horizon and is dated at 11.509Ma in the Leg 154 research (Table 1). The LO of *D. patulus* has been calibrated to a GoM stratigraphic horizon marked by the HO of *Helicosphaera mediterranea*, which has been dated at 17.425Ma (Boesiger *et al.*, 2017; this volume). In the Leg 154 research, the species ranges sporadically down to Sample 928B-27X-CC. 30–32cm (17.347Ma; error 0.036Ma).

##### *Discoaster ulnatus* de Kaenel & Bergen, sp. nov.

Pl. 4, figs 16–19

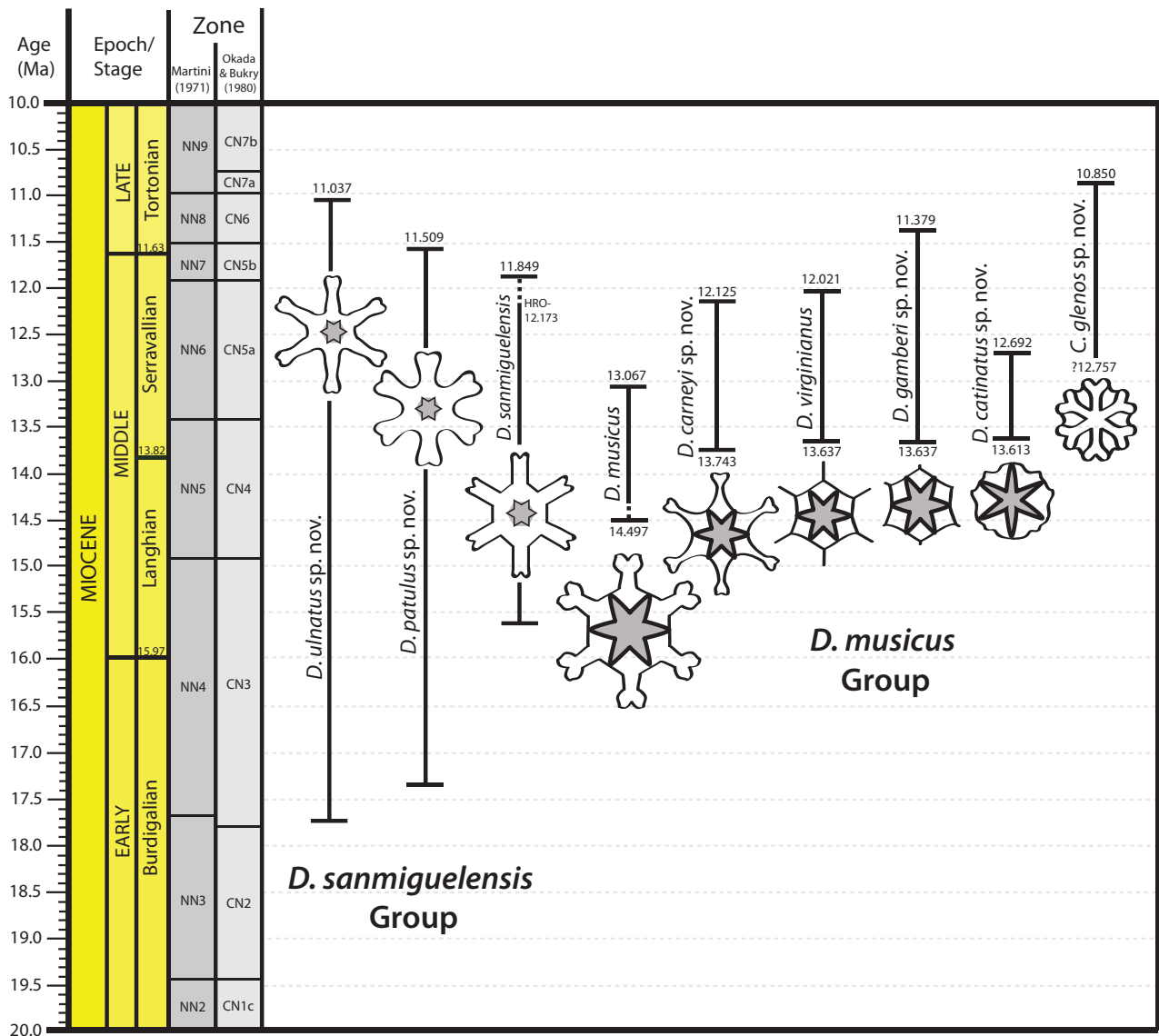
1981 *Discoaster sanmiguelensis* Bukry (*pro parte*), p. 462, pl. 2, fig. 7; pl. 3, figs. 1, 4–7, 11, 12; *non* pl. 2, figs. 8–10; pl. 3, figs. 2, 3, 8–10, 13–14

**Derivation of name:** From Latin *ulna*, meaning forearm and *atus*, meaning having the nature of

**Diagnosis:** A species of the *D. sanmiguelensis* group with relatively long rays that taper to form clubbed terminations.

**Description:** A small to medium-sized *Discoaster* species with a large ornate central area and relatively long tapered rays. The free rays taper to form narrow bifurcations with rounded peripheries. The free ray length is about equal to the central area width. A stellate, distal stem projects between the rays and does not reach the central area periphery; pitted depressions surround this stellate stem. Size = 8–15µm.

**Remarks:** *Discoaster ulnatus* has the longest rays of the three species placed in the *Discoaster sanmiguelensis* group.



**Figure 4:** Range diagram of the *Discoaster sanmiguelensis* and *D. musicus* groups. Ranges and new ages for the NN (Martini, 1971) and CN (Okada & Bukry, 1980) zonations are derived from calibrations in ODP Leg 154 core samples as well as the Gulf of Mexico

The rays of *D. patulus* flare and those of *D. sanmiguelensis* are parallel-sided. *Discoaster patulus* has been referred to as “*D. aff. sanmiguelensis*” in the BP GoM lexicon.

**Holotype dimension:** 11.2  $\mu$ m

**Holotype:** Pl. 4, figs 17–18

**Type locality:** South Trinidad, Bolli (1957)

**Type level:** Sample JS32, *Globorotalia fohsi lobata* Zone, Cipero Formation, Zone NN6

**Occurrence:** The HO of *D. ulnatus* is dated at 11.037Ma (Table 1); it marks a prominent GoM stratigraphic horizon along with the HO of *D. emblematicus* and HO of *D. cuspidatus*. The LO of *D. ulnatus* is associated with a GoM stratigraphic horizon in uppermost Zone NN3 marked by a flood of very small *Reticulofenestra* in four deep-water GoM wells; this horizon has been dated at 17.713Ma (Sample 928B-28X-5, 30–31cm; error 0.021Ma) in the Leg 154 research. The LO of the

*D. ulnatus* has been placed in Sample 928B-28X-5, 65–67cm (17.731Ma; error 0.021Ma) in the Leg 154 research.

#### *Discoaster sanmiguelensis* Bukry, 1981

Pl. 4, figs 15, 20

1981 *Discoaster sanmiguelensis* Bukry (*pro parte*), p. 462, pl. 2, figs. 8, 10; pl. 3, figs. 2, 3, 8–10, 13–14; *non* pl. 2, figs. 7, 9; pl. 3, figs. 1, 4–7, 11, 12

**Remarks:** The light photographs of *D. sanmiguelensis* illustrated by Bukry (1981) encompass what we consider the *D. sanmiguelensis* group herein. The holotype (10.2  $\mu$ m) has parallel-sided rays that form angular inter-ray areas, resulting in a hexagonal central area periphery (upon focus). A stellate, distal stem projects between the rays and does not reach the central area periphery. The size range for this species is between 7–15  $\mu$ m. *Discoaster sanmiguelensis* is distinguished from *D. patulus* and



*D. ulnatus* by its parallel-sided rays and hexagonal central area periphery.

**Occurrence:** The LO of *D. sanmiguelensis* has been calibrated to the LO of *D. petaliformis* in several deep-water GoM wells. In Leg 154, the LO of *D. sanmiguelensis* is dated at 15.617Ma (Sample 925D-37H-1, 140–141cm; error 0.020Ma). Both the HO (11.849Ma) and the HRO (12.173Ma) of *D. sanmiguelensis* are GoM markers calibrated to the Leg 154 research (Table 1).

#### 4.5 *Discoaster musicus* group

*Discoaster musicus* and *D. sanmiguelensis* are both characterized by parallel-sided rays, resulting in a hexagonal central area periphery, and narrow, rounded bifurcations. *Discoaster musicus* appeared about 1.1 million years after *D. sanmiguelensis*, its likely ancestor. *Discoaster musicus* differs from *D. sanmiguelensis* only by the extension of its distal stellate stem to the central area periphery. The *D. musicus* group is characterized herein by this extended distal stem (convex side of the asterolith). Ray morphology distinguishes the five species included in this group; three new species are described (Figure 4). The evolution of the group is well constrained in the Leg 154 research (Figure 4), involving: the thinning of rays (*D. carneyi*), elimination of the bifurcation (*D. virginianus*), shortening of the pointed ray (*D. gamberi*), and elimination of rays (*D. catinatus*). The species are arranged from the bottom of Plate 4 (*D. musicus*) to the middle of Plate 5 (*D. catinatus*) to reflect this evolution. Only the stratigraphic range of *D. musicus* is well constrained in both the GoM and Leg 154 research (Table 1).

##### *Discoaster musicus* Stradner, 1959

Pl. 4, figs 21–25

1959 *Discoaster musicus* Stradner, p. 1088, fig. 28

1961 *Discoaster musicus* Stradner 1959; Stradner in Stradner & Papp (*pro parte*), p. 85, pl. 17, figs. 7a–b, 8a–b, 10; text fig. 8/22; *non* pl. 17, figs. 4a–b, 5a–b, 9a–b; pl. 18, figs. 2a–b

2010 *Discoaster musicus* Stradner 1959; in Stradner, Aubry & Bonnemaïson, p. 17, text figs. 9a–b

**Remarks:** The holotype of *D. musicus* from Stradner (1959) are two drawings (proximal and distal sides). Stradner *et al.*, (2010) re-illustrated the holotype drawings (text fig. 9a), along with four light photomicrographs of the holotype (text fig. 9b). The holotype has a hexagonal central periphery and parallel-sided rays. Stradner *et al.*, (2010) also described that: (1) “the tips of large central star on the concave face can be seen as extra interstitial corners of the central disc” - the star reaches the central area periphery; and (2) the convex face “can be decorated by an additional star”. The holotype of *D. musicus* corresponds to two specimens illustrated on Plate 4 (figs 21–24); the third specimen illustrated on Plate 4 (fig 25) is considered transitional because the rays taper and the central area periphery is not hexagonal. The type locality for the

species is Frättingsdorf, Austria. Stradner & Papp (1961) stated that the type level is lower Tortonian. We have some doubt about this age assignment, as the type material also contains planktonic foraminifera (*P. glomerosa*, *G. bisphaericus* and *O. suturalis*) indicative of the Langhian and lower Zone NN5. *Discoaster musicus* is distinguished from other species of *Discoaster* with large hexagonal central area peripheries by its prominent stellate stem that extends to the edge of the central area between the parallel-sided rays.

**Occurrence:** The HO of *D. musicus* is a GoM marker calibrated to the Leg 154 research and dated at 13.067Ma (Table 1). The LO of *D. musicus* has been associated with the base acme *Cyclicargolithus bukryi* and basal Zone NN5 (see Boesiger *et al.*, 2017; this volume) in multiple deep-water GoM wells. In Leg 154, the LO of *D. musicus* has been observed in lower Zone NN5 and dated at 14.497Ma (Table 1). *Discoaster musicus* has been observed down into Zone NN4 in three deep-water wells, but these occurrences are believed to be transitional specimens with tapered rays.

##### *Discoaster carneyi* de Kaenel & Bergen, sp. nov.

Pl. 4, figs 26–30

1993 *Discoaster* sp. cf. *musicus*, Aubry, p. 364, pl. 3, figs. 9–10

**Derivation of name:** In honor of foraminifera specialist James “Chip” Carney, former BP-Amoco colleague (Houston, TX, USA)

**Diagnosis:** A species of the *D. musicus* group having slender, tapered rays with simple bifurcations.

**Description:** A medium-sized *Discoaster* species with thin, slender rays which taper and then flare to form simple, delicate bifurcations. The large central area contains a stellate distal stem which extends to the central area periphery between the rays. Central area width and ray length are approximately equal. A small proximal knob is present.

**Remarks:** Within the *D. musicus* group, *D. carneyi* is distinguished by having thin, tapered rays with simple bifurcations. The delicate nature of these bifurcations can make *D. carneyi* difficult to distinguish from *D. gamberi* and *D. virginianus* in poorly-preserved material; those two species have thinly pointed rays. *Discoaster musicus* has wider, parallel-sided free rays with clubbed terminations. *Discoaster carneyi* has been referred to as “*D. musicus* (delicate)” in the BP GoM lexicon.

**Holotype dimension:** 9.2µm

**Holotype:** Pl. 4, figs 26–27

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

**Type level:** Sample 926A-29-4, 19–21cm (13.499Ma), Zone NN5

**Occurrence:** *Discoaster carneyi* ranges from upper Zone NN5 (926A-29H-7, 2.4–4.4cm) to upper Zone NN6 (Sample 926A-27H-1, 22–24cm) in the Leg 154 research,

dated from 13.743Ma (error 0.013Ma) to 12.125Ma (error 0.072Ma). The stratigraphic range of *D. carneyi* is not well established in the GoM. The HO of *D. carneyi* has been observed in basal to middle Zone NN6 in six wells, whereas the LO has been noted in upper Zone NN5 in a single deep-water GoM well.

***Discoaster virginianus* (Self-Trail, 2014) de Kaenel & Bergen, emended, comb. nov.**

Pl. 5, figs 1–4

1993 *Catinaster* sp., Aubry, p. 364, pl. 3, figs. 13–15

2014 *Catinaster virginianus* Self-Trail (*pro parte*), p. 53, pl. 2, fig. 1; *non* pl. 1, figs. 1–12; pl. 2, figs. 2a–b

**Emended diagnosis:** A small to medium-sized *Discoaster* species with delicate long, pointed rays. On the distal side, a thick stellate stem extends to the periphery of the central area between the rays. A proximal knob is present.

**Remarks:** The holotype of *C. virginianus* is re-illustrated on Plate 5 (fig. 1). This specimen has thin, pointed rays and a stellate stem that extends to the central area periphery. The species is transferred to the genus *Discoaster*. The holotype takes precedence over the diagnosis and description; it is considered a different species than all other specimens illustrated by Self Trail (2014), which represent three species described herein. The slender rays are not to be confused with spines. *Discoaster virginianus* has been referred to as “*D. musicus* (pointed)” and later as “*D. gamberi*” in the BP GoM lexicon. These two taxa were not differentiated within BP GoM well analyses until recently. It is differentiated from *D. gamberi* herein by having longer rays.

**Occurrence:** *Discoaster virginianus* ranges from upper Zone NN5 (926A-29H-5, 125–127cm) to upper Zone NN6 (Sample 926A-26H-6, 125–127cm) in the Leg 154 research, dated from 13.637Ma (error 0.011Ma) to 12.021Ma (error 0.018Ma). *Discoaster virginianus* (*D. musicus* “pointed”) ranges from upper Zone NN4 to middle Zone NN6, as established in four deep-water GoM wells and includes the concept of another species with pointed ray terminations (*D. gamberi*). The range of Zone NN5 to Zone NN8 for *D. virginianus* given by Self-Trail (2014) is not applicable to our restricted and emended concept of the species.

***Discoaster gamberi* de Kaenel & Bergen, sp. nov.**

Pl. 5, figs 5–10

1993 *Catinaster* sp., Aubry, p. 364, pl. 3, figs. 17–19

2008 *Catinaster* sp. “A”, Denne, p. 239, pl. 2, fig. 5a; *non* pl. 2, fig. 5b

2014 *Catinaster virginianus*, Self-Trail, p. 53, pl. 1, figs. 1–2; *non* pl. 1, figs. 3–12; pl. 2, figs. 1–2

**Derivation of name:** In honor of foraminifera specialist James Gamber, former BP-Amoco colleague (Houston, TX, USA)

**Diagnosis:** A species of the *D. musicus* group with short, slender rays which taper to points.

**Description:** A small to medium-sized *Discoaster* species with very short pointed rays. The large central area contains a stellate distal stem which extends to the central area periphery between the rays. Central area width is much greater than ray length. A small proximal knob is present.

**Remarks:** *Discoaster gamberi* is distinguished from *D. virginianus* by its shorter rays and *D. catinatus* by the presence of very short rays. *Discoaster gamberi* has been referred to as *D. brevigamberi* in the BP GoM lexicon and earlier within the concept of “*D. musicus* (delicate)”. This early concept also included the other species with pointed rays, *D. virginianus*.

**Holotype dimension:** 6µm

**Holotype:** Pl. 5, figs 9–10

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

**Type level:** Sample 926A-29H-2, 141–143cm (13.429Ma), Zone NN5

**Occurrence:** *Discoaster gamberi* ranges from upper Zone NN5 (926A-29H-5, 125–127cm) to lower Zone NN8 (Sample 926B-25H-6, 113–115cm) in the Leg 154 research, dated from 13.637Ma (error 0.011Ma) to 11.379Ma (error 0.024Ma). The stratigraphic range of *D. gamberi* is poorly established in the GoM. The HO of *D. gamberi* has been associated with the HO of *D. deflandrei* in only one BP GoM deep-water exploration well; this stratigraphic horizon in uppermost Zone NN7 has been dated at 11.575Ma (Table 1).

***Discoaster catinatus* de Kaenel & Bergen, sp. nov.**

Pl. 5, figs 11–20

2008 *Catinaster* sp. “A”, Denne (*pro parte*), p. 239, pl. 2, fig. 5b; *non* pl. 2, fig. 5a

2014 *Catinaster virginianus* Self-Trail (*pro parte*), p. 53, pl. 1, figs. 3–12; *non* pl. 1, figs. 1–2; pl. 2, figs. 1–2

**Derivation of name:** From Latin *catinus*, meaning deep vessel, pot

**Diagnosis:** A species of the *D. musicus* group with a serrate periphery and no rays.

**Description:** A small to medium-sized *Discoaster* species without rays. The serrate central area periphery is rounded. It contains a stellate distal stem which extends to the central area periphery. A thick proximal knob is present.

**Remarks:** *Discoaster catinatus* does not have the typical basket-like structure of the genus *Catinaster*, but has a thick proximal knob typical of *Discoaster*. It may be transitional between the two genera. The absence of rays distinguishes it from other members of the *D. musicus* group. *Discoaster catinatus* has been referred to as “*D. musicus* (serrate)” in the BP GoM lexicon. All four specimens illustrated herein were recovered from the same sample.

**Holotype dimension:** 6.8µm

**Holotype:** Pl. 5, figs 16–18

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

**Type level:** Sample 926A-29-5, 80–82cm (13.613Ma), Zone NN5

**Occurrence:** *Discoaster catinatus* ranges from upper Zone NN5 (926A-29H-5, 80–82cm) to middle Zone NN6 (Sample 926A-27H-6, 138–140cm) in the Leg 154 research, dated from 13.613Ma (error 0.024Ma) to 12.692Ma (error 0.031Ma). The HO of *D. catinatus* has been associated with the HRO of *D. sanmiguelensis* in four deep-water GoM wells. This stratigraphic horizon in upper Zone NN6 has been dated at 12.173Ma (Table 1). The LO has been observed in upper Zone NN5 in proximity to the HO of *D. petaliformis* (Table 1) in three deep-water GoM wells.

#### 4.6 *Discoaster micros* group

This group is characterized by “flat” ray bifurcations and ranges from upper Zone NN4 to Zone NN9 (Figure 5). The *Discoaster micros* group includes six species, four of which are described as new. The two described species, *D. micros* and *D. transitus*, have featureless central areas and the youngest extinctions within the group. The two new species with featureless central areas, *D. arneyi* and *D. premicros*, are the two oldest representatives of the group; the stratigraphic ranges of these two closely-related species are well-utilized in the GoM framework and calibrated to the Leg 154 research (Table 1). The remaining two new species, *D. catillomicros* and *D. stellimicros*, have ornate central areas and bridge the stratigraphic gap between the other two pairs of species. The older and younger pairs of species are each differentiated morphologically by their free ray length.

##### *Discoaster premicros* de Kaenel & Bergen, sp. nov.

Pl. 5, figs 21–23

2008 *Discoaster* cf. *D. lidzi*, Denne, p. 238, pl. 1, fig. 4

**Derivation of name:** From Latin *prae*, meaning, before; from Greek *mikros*, meaning small, little

**Diagnosis:** A thick species of the *D. micros* group with short rays, flat bifurcations and a featureless central area.

**Description:** A small, thick *Discoaster* species with six very short, flaring rays that terminate in obtuse bifurcations that are nearly orthogonal to the ray direction. The rays are broad, and their length is less than the central area width. The large central area is thick and devoid of any structures. Specimens show distinct optical contrast with the mounting medium (in plan light) due to their thickness.

**Remarks:** *Discoaster arneyi* has longer rays and slightly lower ray bifurcation angles than *D. premicros*; it is likely ancestral to *D. premicros*. *Discoaster stellimicros* has a central stem. *Discoaster premicros* has been referred to as “*D. aff. micros*” in the BP GoM lexicon.

**Holotype dimension:** 6.0µm

**Holotype:** Pl. 5, figs 21–22

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

**Type level:** Sample 925C-35-3, 120–122cm (14.617Ma), Zone NN5

**Occurrence:** Both the LO and HO of *D. premicros* are utilized in the GoM, dated at 15.498Ma (upper NN4) and 14.189Ma (middle NN5), respectively, in the Leg 154 research (Table 1). The HRO and first down-hole increase (INC) in this Langhian species are also utilized as GoM markers in Zone NN5 and calibrated to the Leg 154 research (Table 1). Denne (2008) noted this taxon as a “flag” for Zone NN5.

##### *Discoaster arneyi* de Kaenel & Bergen, sp. nov.

Pl. 5, figs 24–25

**Derivation of name:** In honor of nannofossil paleontologist James Arney (Bugware Inc., Tallahassee, FL, USA)

**Diagnosis:** A thick species of the *D. micros* group with long rays, nearly flat bifurcations and a featureless central area.

**Description:** A thick, small to medium-sized species of *Discoaster* with six relatively long rays. The rays flare slightly and terminate in simple bifurcations. The ray bifurcations are broad and form an obtuse angle. Ray length is greater than the central area width, and their junctures tend to be angular. The central area is thick and devoid of any structures. Specimens show distinct optical contrast with the mounting medium (in plan light) due to their thickness. Size ranges from 7–11µm.

**Remarks:** *Discoaster premicros* is another thick species from the *D. micros* group, but has much shorter free rays which terminate in flatter bifurcations. *Discoaster deflandrei* has flared arms which terminate in more complex, ‘wrench’-like bifurcations. *Discoaster arneyi* has been referred to as “small *D. aff. deflandrei*” in the BP GoM lexicon.

**Holotype dimension:** 7.6µm

**Holotype:** Pl. 5, fig. 24

**Type locality:** MC 771, Mississippi Canyon, Gulf of Mexico.

**Type level:** middle Zone NN5

**Occurrence:** *Discoaster arneyi* ranges nearly the entire Langhian. Both the LO and HO of *D. arneyi* are utilized in the GoM, dated at 15.857Ma and 14.091Ma, respectively, in the Leg 154 research (Table 1).

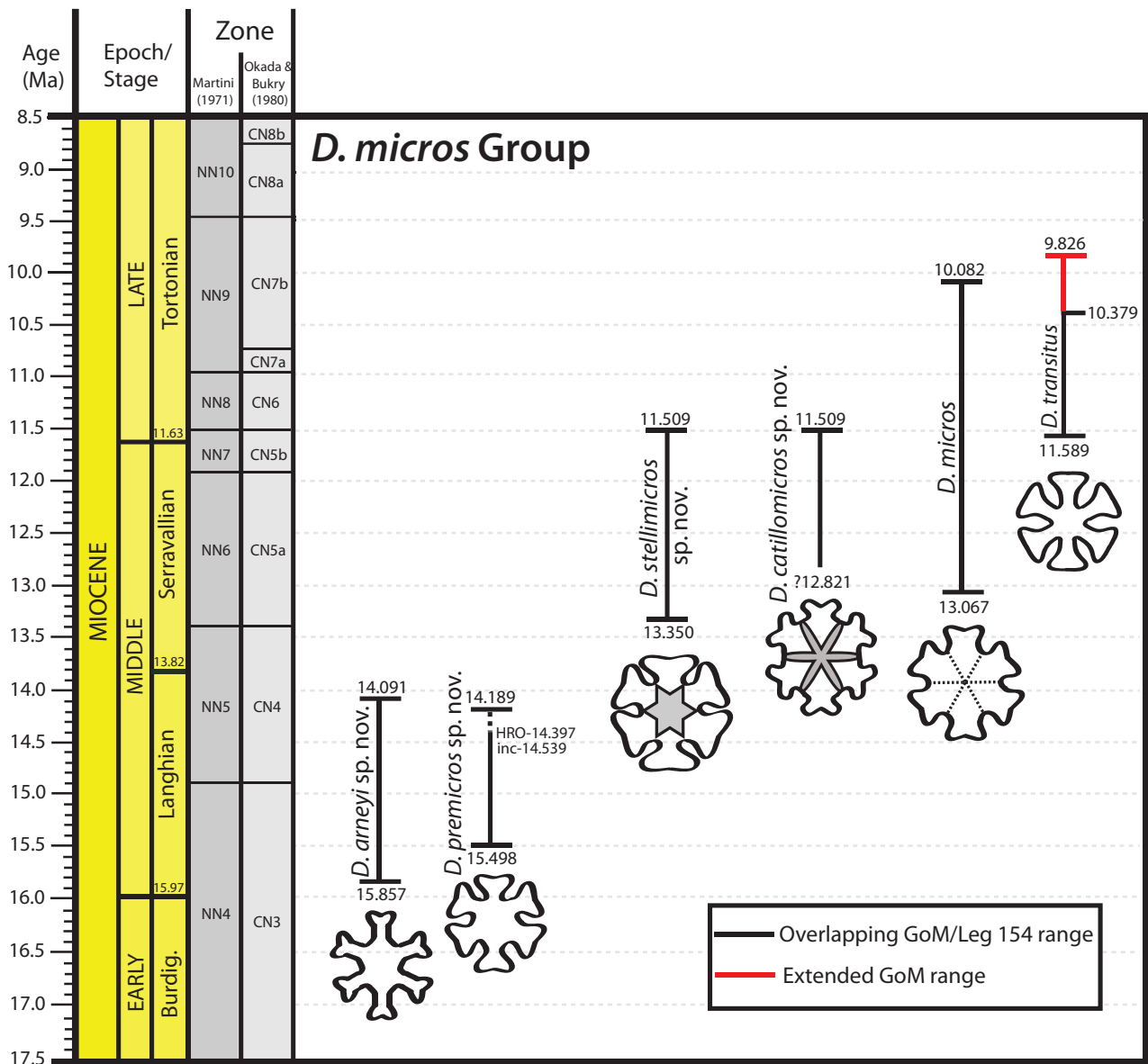
##### *Discoaster stellimicros* Pospichal & Bergen, sp. nov.

Pl. 5, figs 26–28

**Derivation of name:** From Latin *stella*, meaning star; Greek *mikros*, meaning small, little

**Diagnosis:** A species of the *D. micros* group with short rays, flat bifurcations and a stellate stem.

**Description:** A small *Discoaster* species with six short, tapering rays that flare and terminate in obtuse bifurcations that are nearly orthogonal to the ray direction. Ray length is less than the central area width. The ray sutures are most visible on the distal side of the large central area. A proximal stellate stem is present and projects between the rays.



**Figure 5:** Range diagram of the *Discoaster micros* group. Ranges and new ages for the NN (Martini, 1971) and CN (Okada & Bukry, 1980) zonations are derived from calibrations in ODP Leg 154 core samples as well as the Gulf of Mexico

**Remarks:** *Discoaster stellimicros* differs from *D. premicros* by having a prominent stellate stem. *Discoaster catillomicros* also has a stellate stem and short, flat rays but is distinguished by its deep central area depressions. *Discoaster stellimicros* has been referred to as “*D. micros* (star)” in the BP GoM lexicon.

**Holotype dimension:** 7.6µm

**Holotype:** Pl. 5, figs 27–28

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

**Type level:** Sample 926A-27-7, 11.5–13.5cm (12.710Ma), Zone NN6

**Occurrence:** *Discoaster stellimicros* ranges from lower Zone NN6 (926A-29H-1, 100–102cm) to lowermost Zone NN8 (Sample 926A-26H-2, 26.5–28.5cm) in the Leg 154 research, dated from 13.350Ma (error 0.010Ma)

to 11.509Ma (error 0.019Ma). The HO of *D. stellimicros* has been associated with the HO of *Discoaster deflandrei* in a single BP GoM well; this stratigraphic horizon in upper Zone NN7 has been dated at 11.575Ma (Table 1).

***Discoaster transitus* Peleo-Alampay, Bukry, Liu & Young, 1998**

Pl. 5, figs 29–30

1998 *Discoaster transitus* Peleo-Alampay, Bukry, Liu & Young, p. 82, pl. 2, figs. 9–11

**Remarks:** *Discoaster transitus* is a small to medium-sized *Discoaster* with a small central area without the distinctive knob and flaring rays that terminate in flat bifurcations. The tips of the bifurcations are close to each other but do not fuse. *Discoaster micros* has shorter rays and a relatively larger central area than *D. transitus*. Peleo-Alampay



*et al.*, (1998) suggested *Discoaster transitus* as ancestral to *Catinaster*, but other ancestors are possible.

**Occurrence:** In Leg 154, *D. transitus* is sporadic in occurrence from Sample 926A-26H-2, 117.5–119.5cm in uppermost Zone NN7 (11.589Ma; error 0.036Ma) to Sample 926B-24H-5, 1–3cm in middle Zone NN9 (10.379Ma; error 0.062Ma). The HO of *D. transitus* has been observed at slightly higher stratigraphic levels in deep-water GoM wells; this event has been associated with the HRO of *Catinaster coalitus* in 9 wells. This stratigraphic horizon in upper Zone NN9 has been dated at 9.826Ma (Table 1).

***Discoaster micros* (Theodoridis, 1984) de Kaenel & Villa, 1996**

Pl. 6, figs 1–6

1984 *Eu-discoaster micros* Theodoridis, p. 170, pl. 36, figs. 1–3

1996 *Discoaster micros* (Theodoridis, 1984) de Kaenel & Villa, p. 124, pl. 6, figs. 9–10

**Remarks:** *Discoaster micros* is a small *Discoaster* with a large, featureless central area and very short bifurcate rays. The bifurcations are flat or with a highly obtuse angle (more than 120°). As with many *Discoaster* species, the central area may have distinct proximal ridges. *Discoaster micros* is distinguished from *D. catillomicros* by the absence of a central stem and from *D. transitus* by having shorter rays and a relatively larger central area. *Discoaster premicros* has the same morphology as *D. micros* but is thicker and much older than *D. micros*.

**Occurrence:** The HO of *D. micros* is coeval in both the GoM and Leg 154 research, where it has been dated in the latter at 10.082Ma (Table 1). The LO of *D. micros* in the GoM has been associated with the HRO of *D. sanmiguelensis* in three deep-water wells and the HRO of *Calcidiscus premacintyreii* in a single well. These two GoM stratigraphic horizons in upper Zone NN6 have been dated at 12.173Ma (Table 1) and 12.321Ma (Boesiger *et al.*, 2017, this volume), respectively. In the Leg 154 research, the LO of the species was observed in mid-Zone NN6 and dated at 13.067Ma (Sample 926A-28H-4, 107.5–109.5cm; error 0.013Ma).

***Discoaster catillomicros* de Kaenel & Bergen, sp. nov.**

Pl. 6, figs 7–10

**Derivation of name:** From Latin *catillus*, meaning deep vessel; Greek *mikros*, meaning small, little

**Diagnosis:** A species of the *D. micros* group with short rays, flat bifurcations and central area depressions which mimic the genus *Catinaster*.

**Description:** A small *Discoaster* species with six short, tapering rays that terminate in obtuse bifurcations that are nearly orthogonal to the ray direction. The rays are broad and their length much less than the central area width. Inter-ray areas are very shallow and rounded. A

stellate distal stem extends to the central area periphery between the rays. Deep central area depressions are present around the stellate stem.

**Remarks:** *Discoaster catillomicros* is similar in size and shape to *D. stellimicros*, but differs by having large central depressions that mimic some *Catinaster* species. *Discoaster catillomicros* differs from *Catinaster* by having free rays. *Discoaster catillomicros* has been referred to as “*D. cf. micros* (star)” and “*Halfnaster*” sp. in the BP GoM lexicon.

**Holotype dimension:** 5.2µm

**Holotype:** Pl. 6, figs 7–8

**Type locality:** South Trinidad, Bolli (1957)

**Type level:** Sample Bo355, *Globorotalia fohsi robusta* Zone, Cipero Formation, Zone NN7

**Occurrence:** The HO of *D. catillomicros* has been associated with the HO of *D. patulus* in five deep-water GoM wells; these two events in lower Zone NN8 are coeval in the Leg 154 research, both dated at 11.509Ma (Table 1). A LO for the species has not yet been established in the GoM. In the Leg 154 research, the LO in mid-Zone NN6 (Sample 926A-28H-1, 86–88cm; 12.821Ma; error 0.019Ma) is not considered reliable.

**4.7 *Discoaster petaliformis* group**

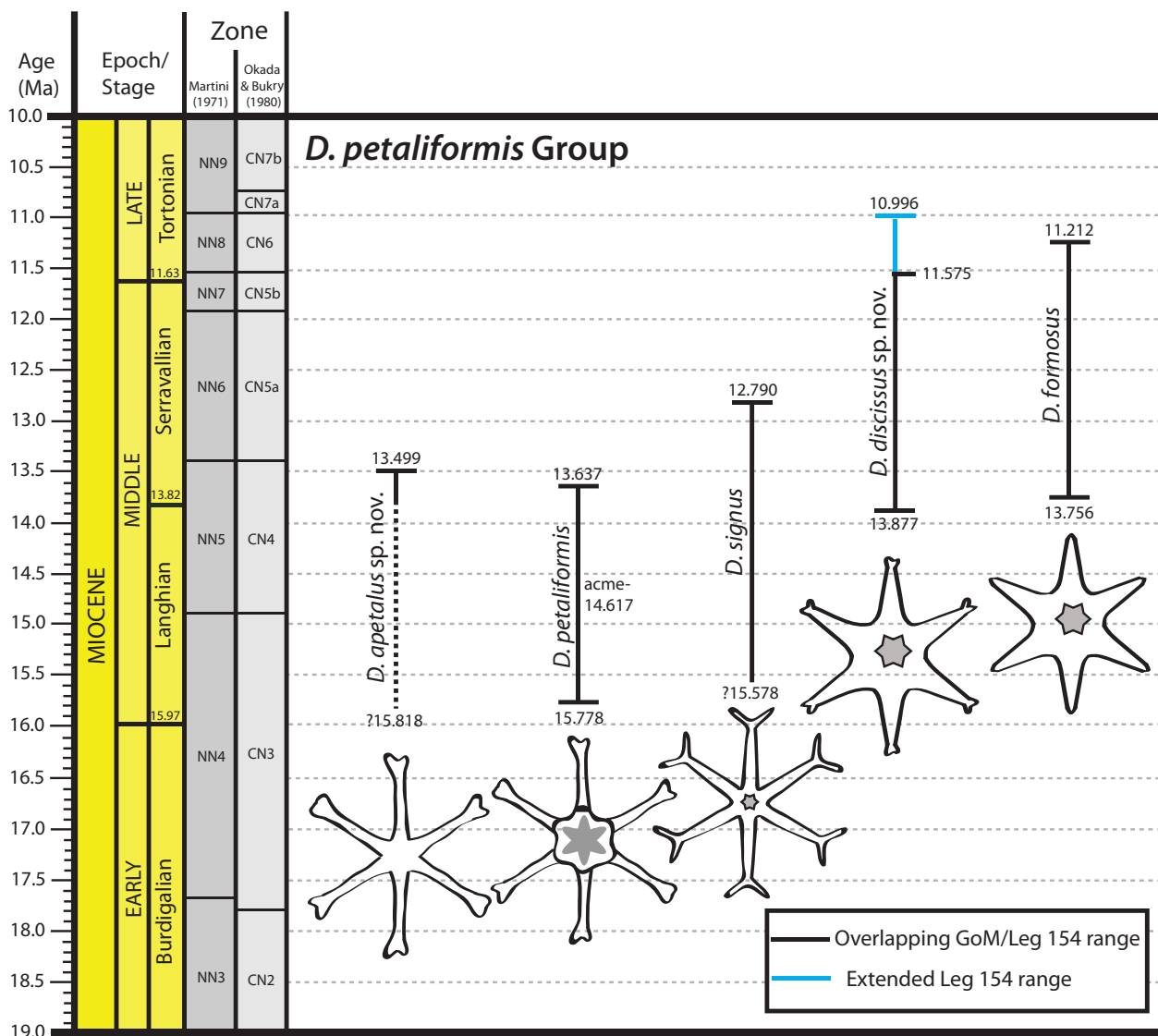
The *Discoaster petaliformis* group includes an assortment of species with high central stems and/or simple bifurcations. Five species are placed in this group (Figure 6), including two new species (*D. discissus* and *D. apetalus*). *D. formosus* is the only species without bifurcate rays but has a high rounded stem. *Discoaster discissus* has the same high rounded stem, but with bifurcate rays. *Discoaster petaliformis* is the only species utilized for GoM stratigraphy (Table 1). *Discoaster signus* and *D. apetalus* have no proven stratigraphic utility in the GoM, but morphologies similar to *D. petaliformis*.

***Discoaster petaliformis* Moshkovitch & Ehrlich, 1980**

Pl. 7, figs 1–8

1980 *Discoaster petaliformis* Moshkovitch & Ehrlich, p. 17, pl. 6, figs. 1–7

**Remarks:** Moshkovitch & Ehrlich (1980) illustrated three specimens of *D. petaliformis* recovered from core taken in a well located on the central coast of Israel. Two of the specimens, including the holotype, were transferred between the light and scanning electron microscopes. All three specimens have high, stellate proximal stems which project down the rays. The holotype has a larger central area and more tapered rays than the other two specimens, which have slender rays and very small centers filled by the stellate stem. These slender forms are more typical of specimens recovered from GoM wells. *Discoaster signus* has a similar morphology, but a very small central area filled only by a high, round knob. The holotype of *D. petaliformis* has a low, round distal knob. *D. apetalus* has no central projection.



**Figure 6:** Range diagram of the *Discoaster petaliformis* group. Ranges and new ages for the NN (Martini, 1971) and CN (Okada & Bukry, 1980) zonation are derived from calibrations in ODP Leg 154 core samples as well as the Gulf of Mexico

**Occurrence:** Both the HO and LO of *D. petaliformis* are utilized in the GoM and dated from 15.778Ma to 13.637Ma in the Leg 154 research (Table 1). The top acme is also utilized as a GoM marker by BP and calibrated by the Leg 154 research (Table 1).

***Discoaster apetalus* de Kaenel & Bergen, sp. nov.**  
Pl. 7, figs 9–11

**Derivation of name:** From Greek: *a-*, meaning not, without; and *petalon*, meaning leaf, petal

**Diagnosis:** A medium to large *Discoaster* having six long, narrow rays with delicate bifurcations and very small central area with no projection.

**Description:** A medium to large *Discoaster* species with six long bifurcate rays. The rays are narrow and are parallel-sided or taper slightly towards the bifurcations. The bifurcations are very thin, and the angle they form is variable. The central area is very small. There is no central projection.

**Remarks:** *Discoaster petaliformis* and *D. signus* are other six-rayed *Discoaster* with morphologies similar to *D. apetalus*, but both these species have central projections. *Discoaster apetalus* has been referred to as “*D. petaliformis* (no stem)” in the BP GoM lexicon.

**Holotype dimension:** 11.6μm

**Holotype:** Pl. 7, figs 9–10

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

**Type level:** Sample 926A-29-4, 116–118cm (13.562Ma), Zone NN5

**Occurrence:** *Discoaster apetalus* was originally distinguished in the Leg 154 research during investigation of the *D. petaliformis* extinction. The HO of *D. apetalus* is well constrained upper Zone NN5 in the Leg 154 research (Sample 926A-29-4, 19–21cm) and dated at 13.499Ma (0.004Ma error), approximately 138ky younger than the extinction of *D. petaliformis* (Table 1). The top of

*D. apetalus* was sequenced above the HO of *D. petaliformis* in one western and two eastern deep-water GoM wells. The LO of *Discoaster apetalus* is not well constrained. It was observed persistently in Leg 154 samples down to Sample 926A-29-7, 63–65cm (13.782Ma) within Zone NN5. Definitive specimens were found as low as Sample 925C-38-1, 130–132cm (15.818Ma) within upper Zone NN4.

***Discoaster signus* Bukry, 1971**

Pl. 7, figs 13–15

1971 *Discoaster signus* Bukry, p. 48, pl. 3, figs. 3–4

**Remarks:** *Discoaster signus* has no proven stratigraphic utility in the GoM, but is included herein because of its morphologic similarity to *D. petaliformis*. *Discoaster signus* has slender, long rays and delicate bifurcations. Bukry (1971) described *D. signus* as having no developed central area and a prominent knob present at the hub of the rays. This knob cannot be seen on the holotype but is clear on the second specimen illustrated by Bukry (1971). *Discoaster petaliformis* has a high stellate stem oriented along its six slender rays, whereas *D. apetalus* has no central projection.

**Occurrence:** A stratigraphic range has not been established for *D. signus* in the GoM. A very distinct HO has been established in the Leg 154 research; this event has been placed within mid-Zone NN6 in Sample 926A-28H-1, 38–40cm (12.790Ma; error 0.033Ma). The LO is in upper Zone NN4.

***Discoaster discissus* de Kaenel & Bergen, sp. nov.**

Pl. 7, figs 12, 16

**Derivation of name:** From Latin *di*, meaning two, in part; and *scissus*, meaning cut, split

**Diagnosis:** A medium to very large *Discoaster* with six long tapering rays with narrow bifurcations and a relatively large central area containing a very high, round knob.

**Description:** A medium to very large *Discoaster* species with a large central area and long, tapering bifurcate rays. The bifurcations are short and narrow. Free ray length is greater than the central area width. A very high, prominent knob is present and has a slightly stellate to rounded outline.

**Remarks:** *Discoaster discissus* and *D. formosus* possess the same high proximal knob, but *D. discissus* has bifurcate rays. Large specimens of *D. decorus* have the same morphology as *D. discissus*, but lack the prominent knob. *Discoaster discissus* has been referred to as “*D. formosus* (bifurcate)” in the BP GoM lexicon.

**Holotype dimension:** 24.0µm

**Holotype:** Pl. 7, fig. 12

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

**Type level:** Sample 926A-29-2, 141–143cm (13.429Ma), Zone NN5

**Occurrence:** *Discoaster discissus* ranges from mid Zone NN5 (926A-30H-1, 79.5–81.5cm) to uppermost

Zone NN8 (Sample 926A-25H-5, 80–82cm) in the Leg 154 research, dated from 13.877Ma (error 0.008Ma) to 10.996Ma (error 0.012Ma). The HO of *D. discissus* has been tied to the HO of *D. deflandrei* in only two GoM wells; this stratigraphic horizon in upper Zone NN7 has been dated at 11.575Ma in the Leg 154 research (Table 1).

***Discoaster formosus* Martini & Worsley, 1971**

Pl. 7, figs 17–20

1971 *Discoaster formosus* Martini & Worsley, p. 1500, pl. 2, figs. 1–8

**Remarks:** Martini & Worsley (1971) stated a size range of 15–19µm for the species; they described a prominent star-shaped knob on one side, although this knob can be somewhat rounded. *Discoaster formosus* is distinguished from other large mid-Miocene *Discoaster* species by its pointed ray tips and prominent, high knob.

**Occurrence:** The HO of *D. formosus* has been calibrated to a local abundance cycle immediately below the GoM stratigraphic horizon marked by the HO of the *D. hexapleuros* (knob), which is dated at 11.155Ma in the Leg 154 research (Table 1). The actual HO of *D. formosus* in the Leg 154 research is in Sample 926A-25H-7, 10–12cm, dated at 11.212Ma (error 0.034Ma). The LO of *D. formosus* has been tied to the HRO of *Cyclicargolithus bukryi* in four GoM wells; this stratigraphic horizon in upper Zone NN5 has been dated at 13.706Ma in the Leg 154 research (Boesiger *et al.*, 2017; this volume). The actual LO of *D. formosus* in the Leg 154 research is in Sample 925B-34H-2, 90–91cm, dated at 13.756Ma (error 0.013Ma).

**4.8 Catinaster group**

**Genus *Catinaster* Martini & Bramlette, 1963**

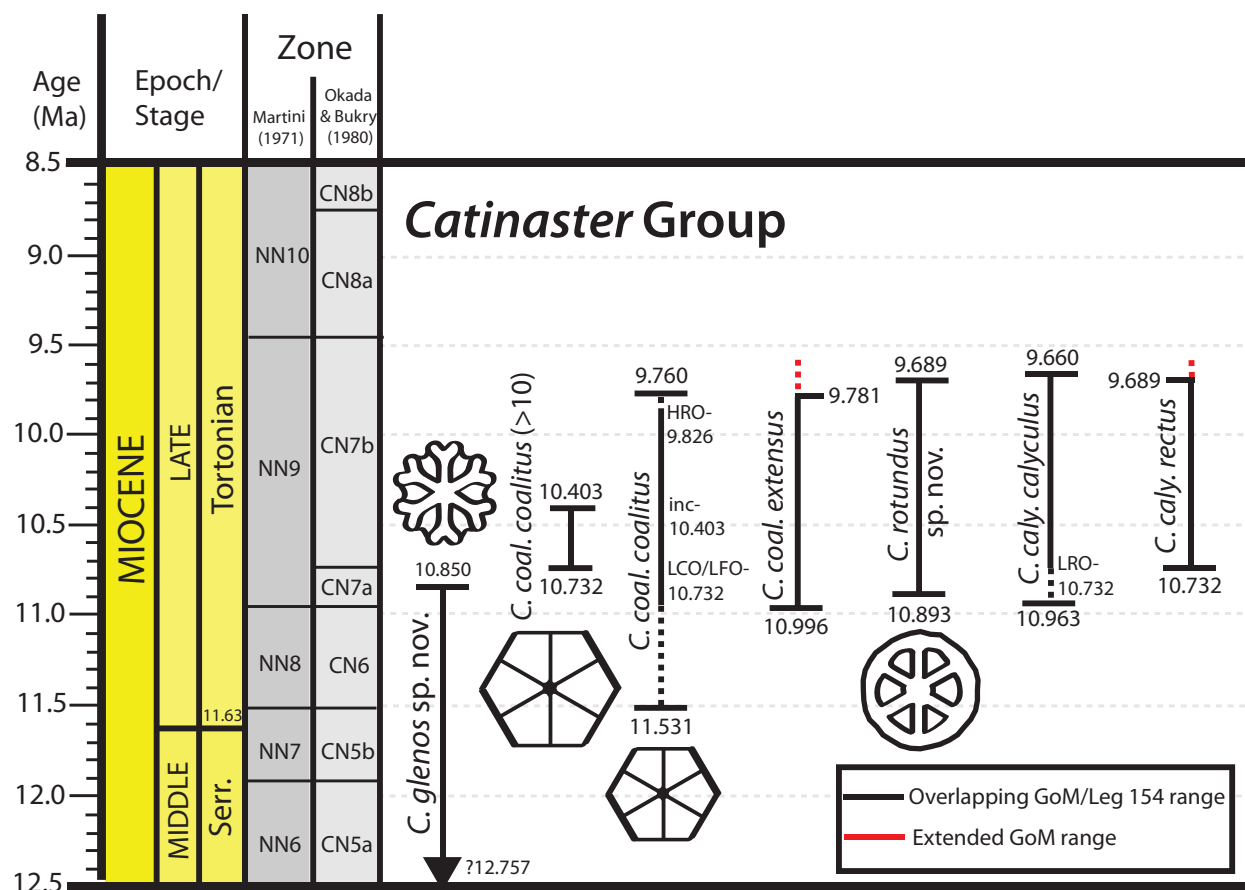
Six *Catinaster* taxa are included herein (Figure 7). *Catinaster calyculus* and *C. coalitus* were described from the upper Miocene of Trinidad by Martini & Bramlette (1963). Peleo-Alampay *et al.*, (1998) erected subspecies for both these species based on the extension and orientation of distal central structures. *Catinaster glenos* and *C. rotundus* are described from the same Trinidad collection (Bolli, 1957) from which the genus *Catinaster* was erected over a half century ago. *Catinaster rotundus*, originally an Arco species, is essentially a round *C. coalitus*. *Catinaster glenos* is possibly the ancestral species of this lineage (Figure 7). Peleo-Alampay *et al.*, (1998) indicated *D. transitus* was ancestral to *Catinaster*, whereas Self-Trail (2014) proposed *D. virginianus* as the ancestral species. The morphology of *C. glenos* appears transitional between *D. virginianus* and *C. coalitus*.

***Catinaster glenos* de Kaenel & Bergen, sp. nov.**

Pl. 6, figs 11–16

2014 *Catinaster virginianus* Self-Trail (*pro parte*), p. 53, pl. 2, figs. 2a–b; *non* pl. 1, figs. 1–12; pl. 2, figs. 1a–b

**Derivation of name:** From Greek *glenos*, meaning thing to stare at, show wonder



**Figure 7:** Range diagram of the genus *Catinaster*. Ranges and new ages for the NN (Martini, 1971) and CN (Okada & Bukry, 1980) zonations are derived from calibrations in ODP Leg 154 core samples as well as the Gulf of Mexico

**Diagnosis:** A basket-shaped *Catinaster* species having thick distal ray bifurcations which touch or nearly touch.

**Description:** Small to medium-sized *Catinaster* species with a basket-like structure (seen in lateral view) and thick distal rays with broad bifurcations. The distal ray bifurcations are thick and form obtuse angles. Their tips are close to each other and may touch occasionally, but do not fuse. In lateral view, the proximal periphery is not quite rounded.

**Remarks:** In lateral view, *C. glenos* has the typical basket-shaped structure of *Catinaster* but is also reminiscent of the proximal stem of many *Discoaster* species (Pl. 6, figs 15–16). *Catinaster glenos* is differentiated from *D. catinatus* by having a very reduced proximal stem, but more easily by having thick, bifurcate distal rays. *Catinaster glenos* is differentiated from *C. coalitus* by these thick, bifurcate distal ray elements. *Catinaster coalitus* has thin distal ray elements with simple, pointed terminations.

**Holotype dimension:** 7.2µm

**Holotype:** Pl. 6, figs 13–14

**Type locality:** South Trinidad, Bolli (1957)

**Type level:** Sample Bo355, *Globorotalia foehi robusta* Zone, Cipero Formation, Zone NN7

**Occurrence:** *Catinaster glenos* was observed sporadically in samples from mid Zone NN6 (926A-27CC,

10–12cm) to lowermost Zone NN9 (Sample 926A-25H-4, 56–58cm) in the Leg 154 research, dated from 12.757Ma (error 0.033Ma) to 10.850Ma (error 0.017Ma). The HO of *C. glenos* has been tied to the HO of *Discoaster hexapleuros* (knob) in three deepwater GoM wells; this stratigraphic horizon in upper Zone NN8 has been dated at 11.155Ma (Table 1).

### *Catinaster coalitus coalitus* Martini & Bramlette, 1963

Pl. 6, figs 17–21

1963 *Catinaster coalitus coalitus* Martini & Bramlette, p. 851, pl. 103, figs. 7–9

**Remarks:** *Catinaster coalitus extensus* is differentiated from *C. coalitus coalitus* by having rays which extend outside the central area periphery. *Catinaster glenos* has thick, bifurcate rays. *Catinaster coalitus* is distinguished from *C. rotundus* by its hexagonal peripheral outline.

**Occurrence:** The LO of the species *C. coalitus* marks the base of Zone NN8 of Martini (1971) and Zone CN6 of Okada & Bukry (1980). This event was difficult to place in the Leg 154 research because specimens are almost always oriented in lateral view, indicating that specimens are taller in the lower part of the stratigraphic range of *Catinaster*. The LO was dated at 11.531Ma in the Leg 154



research (Table 1), comparable to its position in deep-water GoM wells. The HO of *C. coalitus* is a GoM marker, but this stratigraphic horizon has been equilibrated to the HRO of *C. coalitus* in the Leg 154 research and dated at 9.826Ma (Table 1). The underlying GoM stratigraphic horizon is marked by the HO of large *C. coalitus* (>10µm) and the first downhole increase in *C. coalitus*. These two events are dated at 10.403Ma, equilibrating the first downhole increase observed in GoM wells to the HCO in the Leg 154 research (Table 1). The LO of large *C. coalitus* corresponds to the LCO of the species in the Leg 154 research, in which these two events are dated at 10.732Ma (Table 1). The LCO of *C. coalitus* has been applied in deep-water GoM wells (Table 1), whereas the LO of large *C. coalitus* is not yet established in the GoM.

***Catinaster rotundus* de Kaenel & Bergen, sp. nov.**

Pl. 6, figs 22–24

**Derivation of name:** From Latin *rotundus*, meaning circular

**Diagnosis:** A small to medium-sized *Catinaster* species. In plan view, the species has a circular peripheral outline and six straight rays that extend from the center to the rim.

**Remarks:** *Catinaster coalitus coalitus* has a hexagonal periphery, whereas *Discoaster catinatus* has a serrate periphery. *Catinaster rotundus* has been referred to as “*C. coalitus* (round)” in the BP/Arco GoM lexicon.

**Holotype dimension:** 6.7µm

**Holotype:** Pl. 6, fig. 22

**Type locality:** South Trinidad, Bolli (1957)

**Type level:** Sample KR23422; *Globorotalia menardi* Zone, Lengua Formation, Zone NN9

**Occurrence:** The HO of *C. rotundus* has been observed immediately below the HO of large *D. hamatus* (>15µm) in two deep-water GoM wells; this stratigraphic horizon in upper Zone NN9 is dated at 9.618Ma in the Leg 154 research (Browning *et al.*, 2017; this volume). *Catinaster rotundus* was observed very sporadically in samples from lower Zone NN9 (926A-25H-4, 107–109cm) to upper Zone NN9 (Sample 926A-24H-1, 75–77cm) in the Leg 154 research, dated from 10.893Ma (error 0.027Ma) to 9.689Ma (error 0.010Ma).

***Catinaster coalitus* Martini & Bramlette, 1963**

***extensus* Peleo-Alampay *et al.*, 1998**

Pl. 6, figs 25–26

1998 *Catinaster coalitus extensus* Peleo-Alampay, Bukry, Liu & Young, p. 83, pl. 1, figs. 8–9; pl. 2, figs. 19–20; pl. 3, figs. 1–6

**Remarks:** *Catinaster coalitus extensus* is differentiated from *C. coalitus coalitus* by having rays which extend outside the periphery.

**Occurrence:** In Leg 154, *C. coalitus extensus* ranges from Sample 926A-25H-5, 80–82cm (10.996Ma; error 0.006Ma) to Sample 926A-24H-2, 139–141cm (9.781Ma; error 0.021Ma). The HO was observed between the HO

of the new species *Discoaster caulifloris* (Browning *et al.*, this volume) and the HO of large *Discoaster hamatus* (>15µm) in three deep-water GoM wells; these two successive *Discoaster* marker events were dated at 9.542Ma and 9.618Ma in the Leg 154 research (Browning *et al.*, 2017; this volume).

***Catinaster calyculus* Martini & Bramlette, 1963**

***rectus* Peleo-Alampay *et al.*, 1998**

Pl. 6, figs 27–28

1963 *Catinaster calyculus* Martini & Bramlette (*pro parte*), p. 850, pl. 103, figs. 2–3; *non* pl. 103, figs. 1, 4–6  
1998 *Catinaster calyculus rectus* Peleo-Alampay, Bukry, Liu & Young, p. 84, pl. 1, figs. 10–15; pl. 3, figs. 7–11

**Remarks:** *Catinaster calyculus rectus* has straight rays, whereas the rays of *C. calyculus calyculus* are curved. *Catinaster coalitus extensus* also has straight rays which extend outside the central periphery but bisect the hexagonal sides of that periphery.

**Occurrence:** *Catinaster calyculus* was not differentiated into subspecies in GoM wells. In Leg 154, it ranges from Sample 926A-25H-3, 67–69cm (10.732Ma; error 0.020Ma) to Sample 926A-24H-1, 75–77cm (9.689Ma; error 0.010Ma).

***Catinaster calyculus calyculus* Martini & Bramlette, 1963**

Pl. 6, figs 29–30

1963 *Catinaster calyculus* Martini & Bramlette (*pro parte*), p. 850, pl. 103, figs. 1, 4–6; *non* pl. 103, figs. 2–3

**Remarks:** *Catinaster calyculus calyculus* has long, curved rays that extend from the corners of the hexagonal basket.

**Occurrence:** In the Leg 154 research, *C. calyculus calyculus* ranges from Sample 926A-25H-5, 44–46cm (10.963Ma; error 0.021Ma) to Sample 926A-24H-1, 10–12cm (9.660Ma; error 0.030Ma). The LRO of *C. calyculus calyculus* was dated at 10.732Ma (Sample 926A-25H-3, 67–69cm; error 0.020Ma) in the Leg 154 research. The HO of the species was observed between the HO of *D. caulifloris* (9.542Ma) and the HO of large *D. hamatus* (9.618Ma) within lower NN10 (Browning *et al.*, 2017; this volume) in four deep-water GoM wells.

## 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 several of the new species herein. Type material from DSDP and ODP cores are also stored at the Bremen repository (Germany) and the College Station repository (USA).

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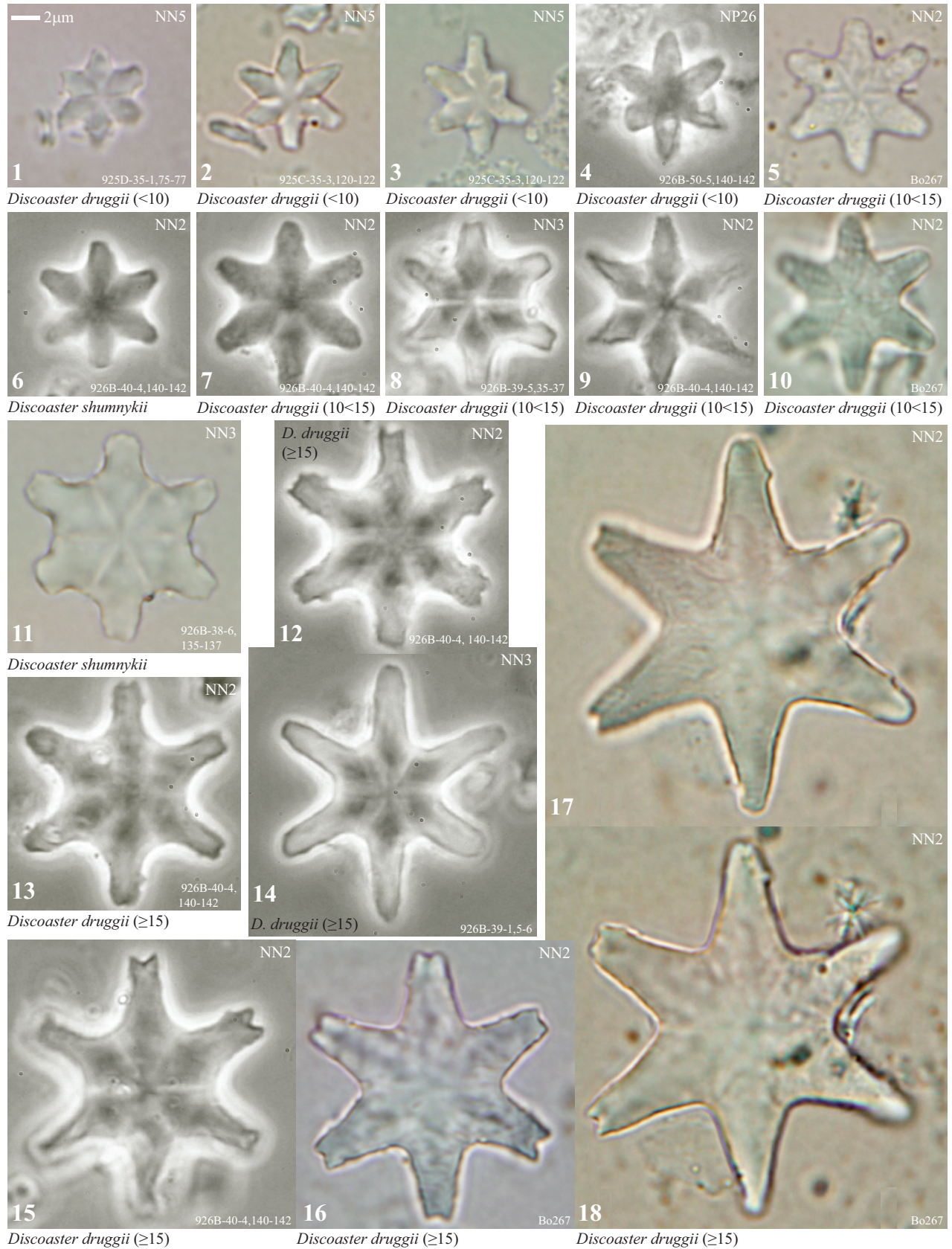
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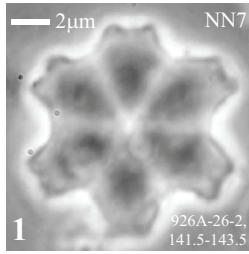


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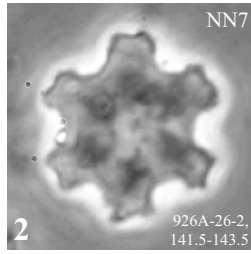




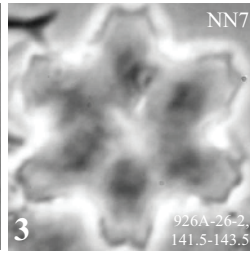
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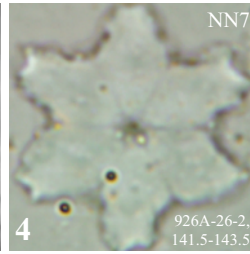
*D. kugleri*



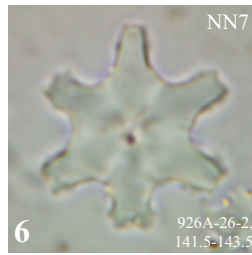
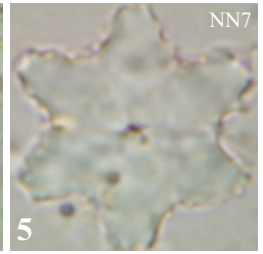
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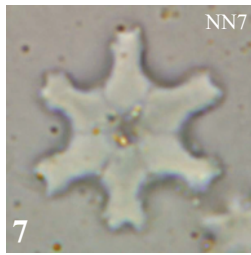
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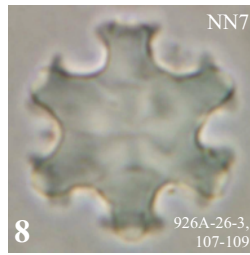
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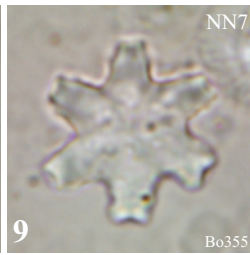
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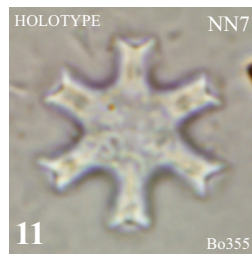
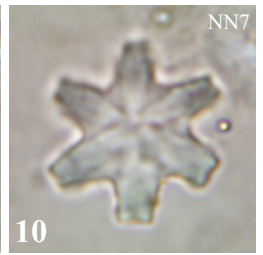
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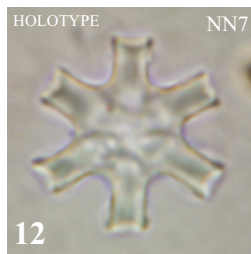
*D. kugleri*



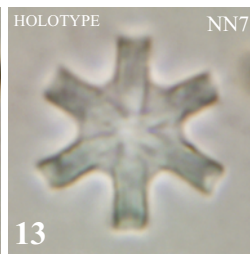
*D. kugleri* (transitional *D. cuspidatus*)



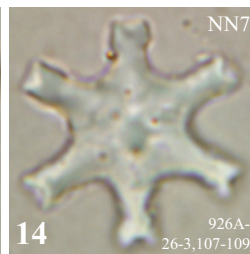
*D. hexapleuros*



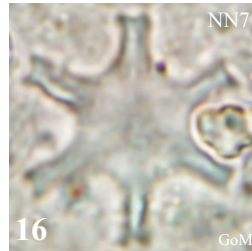
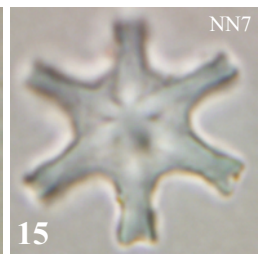
*D. hexapleuros*



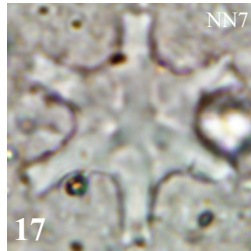
*D. hexapleuros*



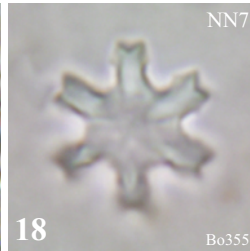
*D. hexapleuros* (knob)



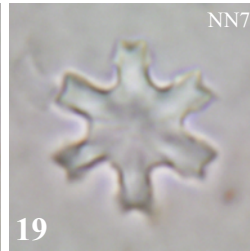
*D. hexapleuros*



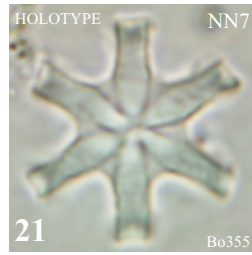
*D. hexapleuros*



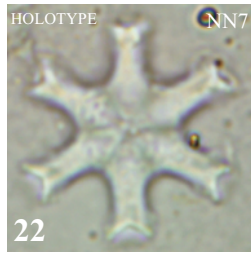
*D. hexapleuros*



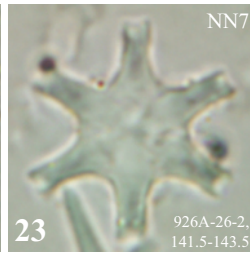
*D. hexapleuros*



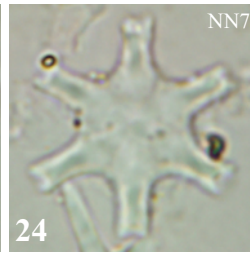
*D. cuspidatus*



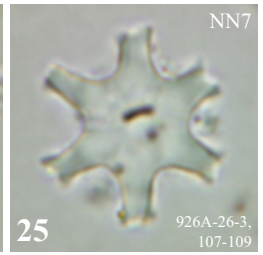
*D. cuspidatus*



*D. cuspidatus*



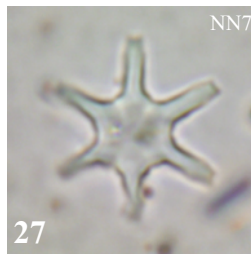
*D. cuspidatus*



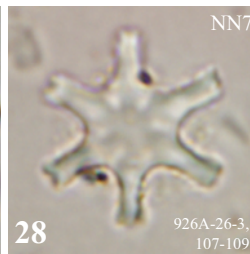
*D. cuspidatus* (knob)



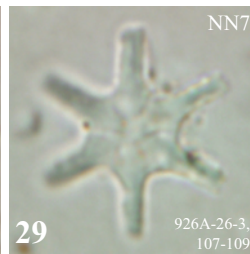
*D. cuspidatus*



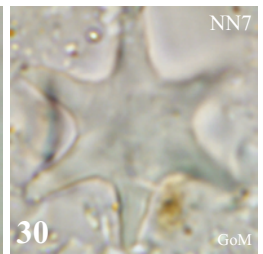
*D. cuspidatus*



*D. cuspidatus*



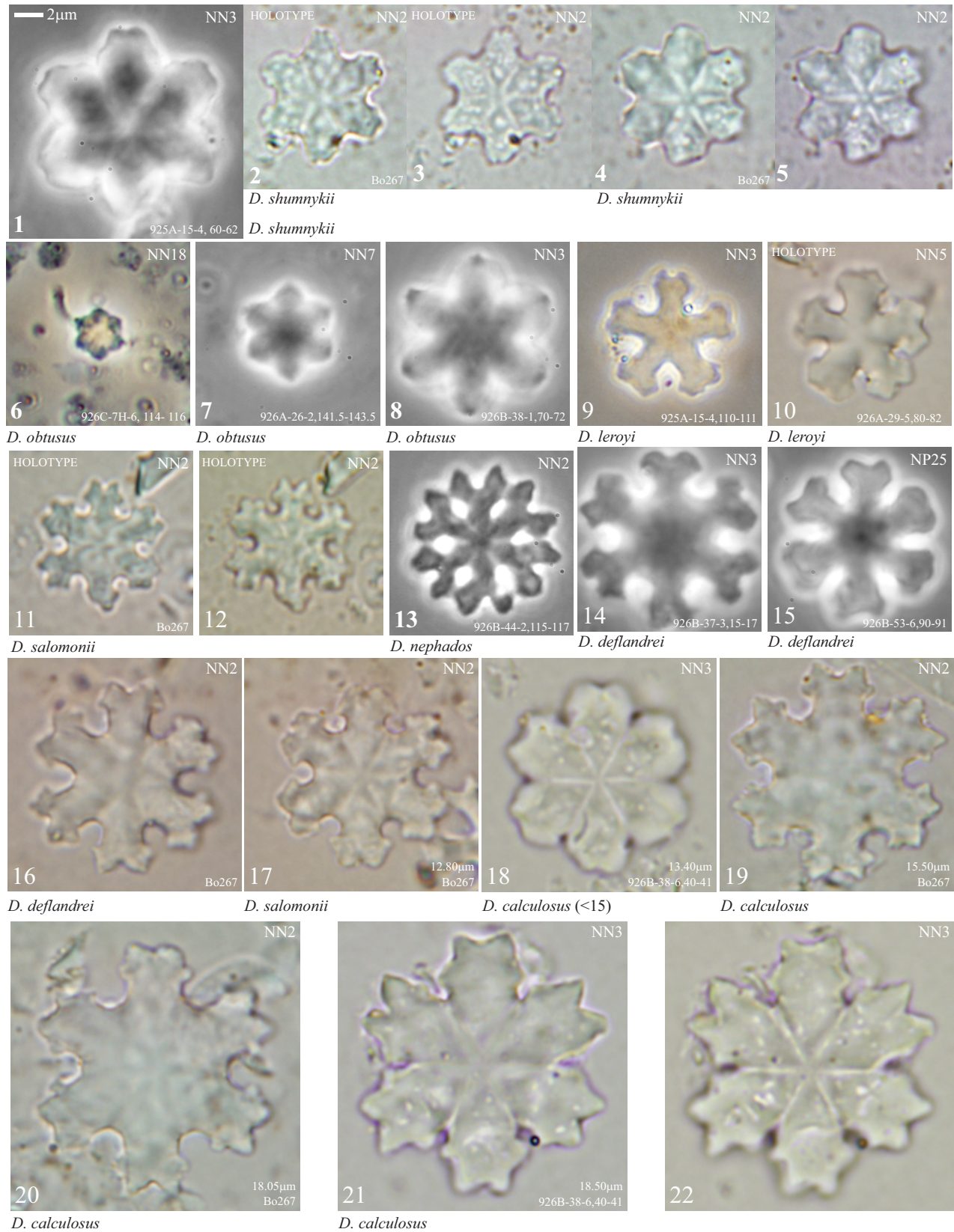
*D. cuspidatus*



*D. cuspidatus*



## Plate 3

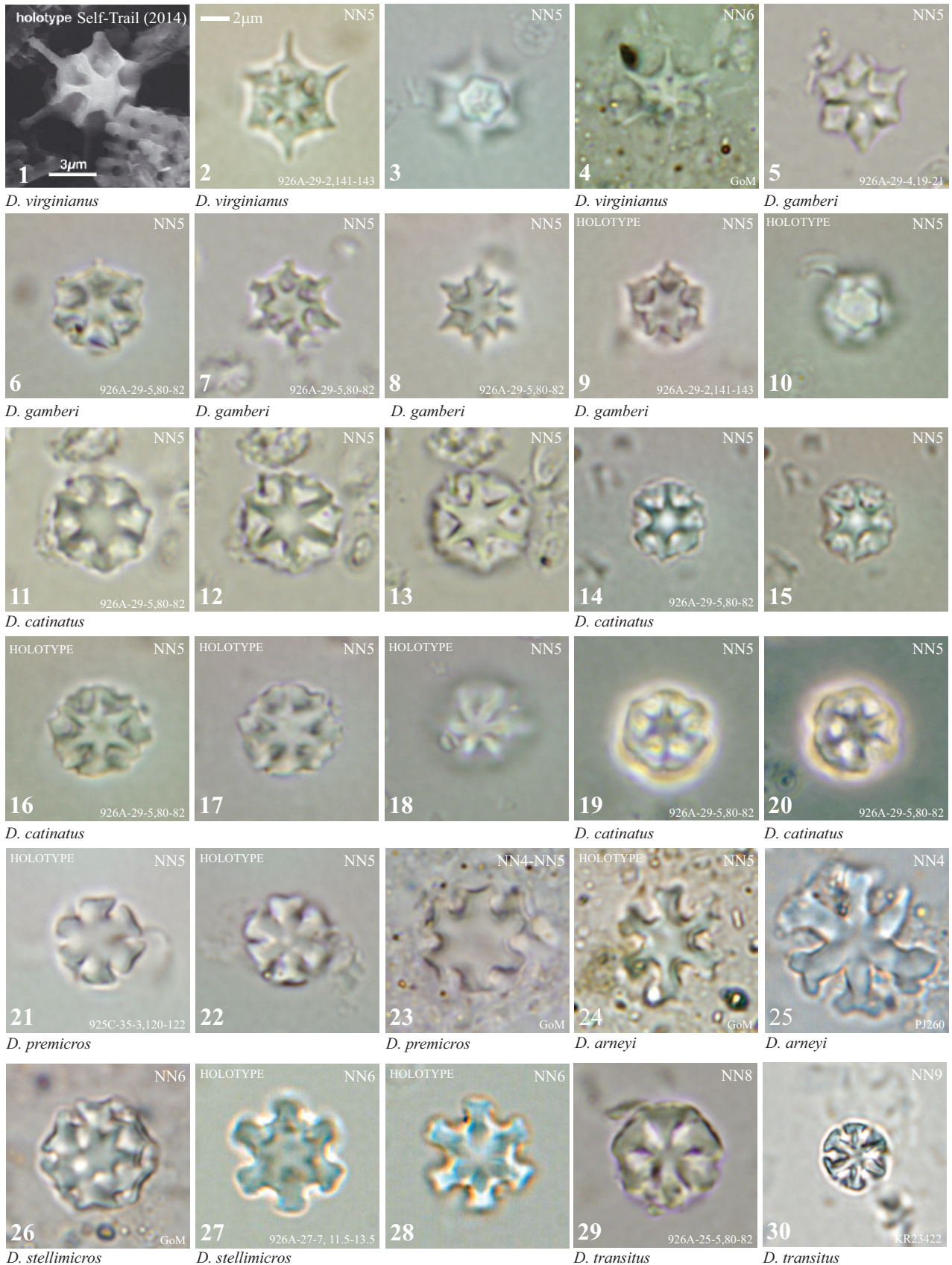




[illegible]

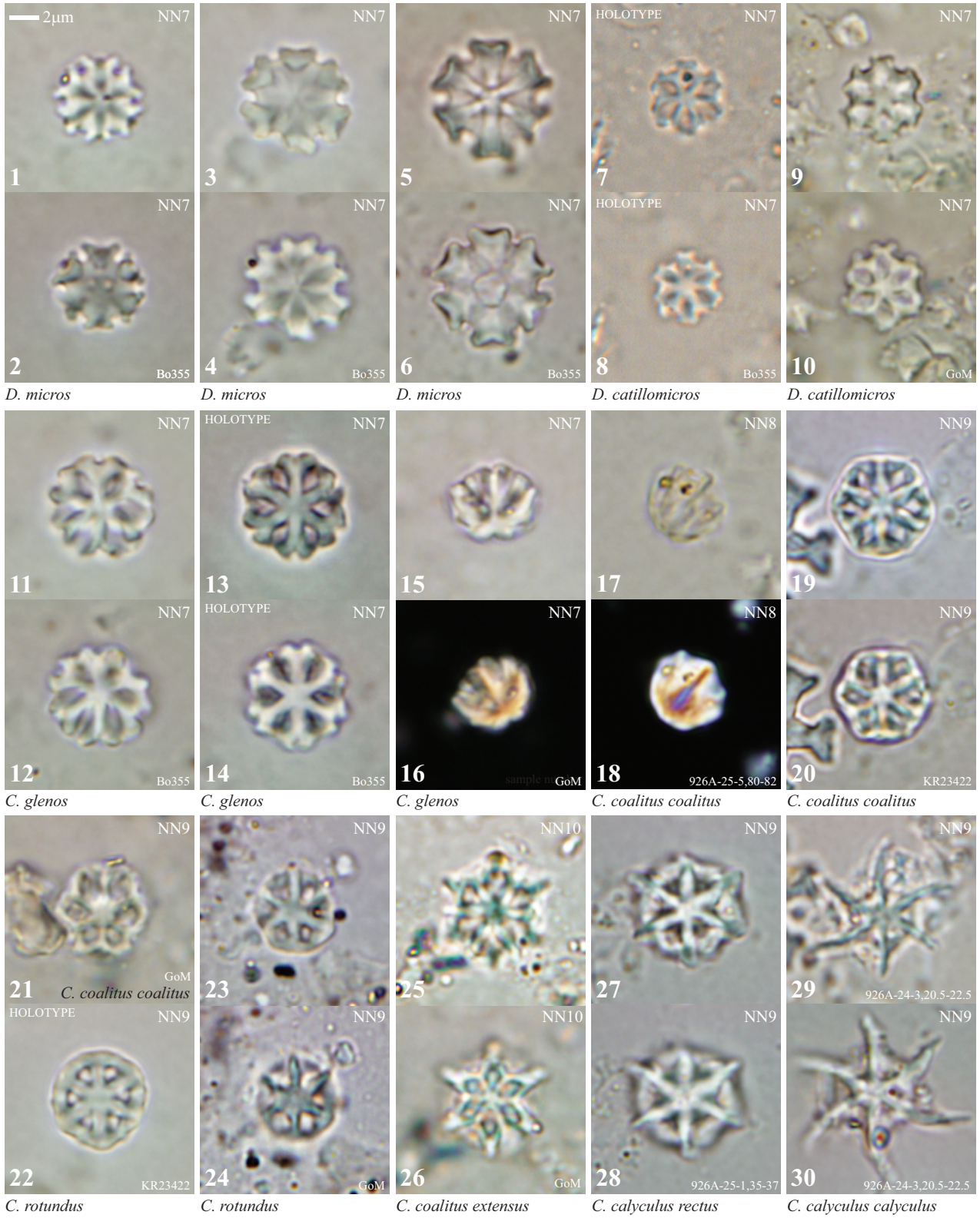


## Plate 5





## Plate 6





## Plate 7

