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Late Miocene to Late Pliocene taxonomy and stratigraphy of the genus *Discoaster* in the circum North Atlantic Basin: Gulf of Mexico and ODP Leg 154

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Abstract *Discoasters* have long been utilized in Neogene nannofossil biostratigraphy in the Gulf of Mexico and make up an important group of marker taxa from the Pliocene to Middle Miocene. In this paper, we discuss taxonomy and biostratigraphy of seven *Discoaster* groups and one group of *Minylitha* for the Late Pliocene to Late Miocene. Detailed taxonomic descriptions of species in these groups are provided with accompanying photographs and morphologic diagrams. Discussions of described species, subspecies, emendations and descriptions of new species provide an education of species concepts utilized by British Petroleum for biostratigraphic control in the Gulf of Mexico. The stratigraphic occurrences of these species are calibrated to the astronomical chronometer from ODP Leg 154 in the western equatorial Atlantic and tied to the Neogene Astronomical Time Scale. Forty-eight biostratigraphic events are discussed for the Gulf of Mexico and ODP Leg 154 from 17.393 to 1.924Ma. Eleven new *Discoaster* and one new *Minylitha* taxa are described: *D. bolivariae, D. breviloeblichii, D. caulifloris, D. pachyloeblichii, D. pansulus, D. pliostellulus, D. quadribollii, D. dennei*, *D. tribollii, D. trifolius, D. triuncinus* and *M. cancellata.* We introduce one new subspecies, *D. prepentaradiatus plautus,* and three taxa emendations: *Discoaster hamatus, Discoaster styzenii* and *Discoaster neohamatus*.

Keywords Nannofossils, Pliocene, Miocene, taxonomy, Gulf of Mexico, biostratigraphy, *Discoaster*, *Minylitha*, ODP Leg 154

1. Introduction

Calcareous nannofossil biostratigraphy has become an increasingly important tool for subsurface description in the petroleum industry over the last few decades with the move to explore and develop deep-water basins. The focus of this study is the application of biostratigraphy in the Gulf of Mexico (GoM). The 1990s mergers of British Petroleum (BP) with Amoco and Arco Vastar provided BP the opportunity to integrate Cenozoic calcareous microfossil biostratigraphies for the Gulf of Mexico developed independently within these three heritage companies. In the early 2000s, to aid exploration efforts and development in stratigraphically- and- structurally complex fields in the Gulf of Mexico, BP supported research to improve their biostratigraphic database. The results from this heritage integration and research were the development of the in-house BP Gulf of Mexico Neogene Astronomically Tuned Time Scale.

A fourteen-year in-house research program was initiated to ground this Cenozoic framework to an "astronomically-tuned" age model by utilizing core material from Ocean Drilling Program (ODP) Leg 154, Ceará Rise. This integrated framework is based on the historical analysis of thousands of wells in the Gulf of Mexico, and is calibrated from Leg 154 core material. This represents a cyclostratigraphic-based age model for the early Oligocene (30.679Ma) through early Pleistocene (1.595Ma). The "BP Gulf of Mexico Neogene Astronomically Tuned Time Scale" (BP GNATTS; Bergen *et al*., in prep) is currently in preparation for publication and contains the details of the BP Gulf of Mexico age model, biostratigraphic horizon nomenclature, and event stratigraphy and calibration (Bergen *et al*., in prep).

The extensive taxonomic and stratigraphic discussion of BP concepts and revisions of Neogene species within the five taxonomic papers presented in this volume are meant to provide a manual for learning and clarifying concepts which must precede publication of the BP GNATTS. These works, in sum, represent over five decades of compiled knowledge in the GoM from within the heritage companies and BP. This paper focuses on species of *Discoaster* nannofossil taxa and events from the Late Pliocene (1.924Ma; NN18) to Middle Miocene (17.373Ma; NN4). It includes biostratigraphic refinement, taxonomic definitions, and new species descriptions primarily of *Discoasters*, but also includes species of *Minylitha*. This study expands upon the two group's biostratigraphic utility by providing 48 biostratigraphic events, 12 new species descriptions, one new subspecies description and three emendations. *Discoaster quinqueramus*, a key group for late Miocene biostratigraphy, has been separated and is discussed by Blair *et al*. (2017; this volume), as well as taxa associated with the Miocene/Pliocene boundary.

2. Materials and methods

The materials used for this study are from outcrops, core and well cuttings. Most of these samples were collected from ODP cores of Leg 154 at the IODP repository in Bremen (Germany), from the Lower Oligocene (30.679Ma) to the Lower Pleistocene (1.595Ma).

ODP Leg 154 is situated on the Ceará Rise in the western tropical Atlantic Ocean. Other DSDP/ODP materials used are from DSDP Leg 68, Hole 502 (Colombia Basin, western Caribbean Sea) and the original Bolli Collection from Trinidad (Figure 1). Details of the sampling program and sample preparation are provided in de Kaenel *et al*. (2017; this volume).

The base of the Pleistocene was moved to the base of the Gelasian Stage in 2009 by the Executive Committee of the International Union of Geological Sciences (IUGS); however, we have decided to keep the Pliocene/Pleistocene boundary at the top of the Gelasian Stage at 1.806Ma, following the astronomically tuned age of Lourens *et al*. (1996). This transfer of the Gelasian Stage is not followed in this regional study because the BP GNATTS (Bergen *et al*., in prep) has not yet adopted the new Pliocene/Pleistocene boundary placement at the top of the Gelasian Stage. This omission is necessary to avoid confusion and maintain consistency with the GoM industry standard that continues to place the boundary at the top of the Gelasian Stage on the last occurrence of *Discoaster brouweri*.

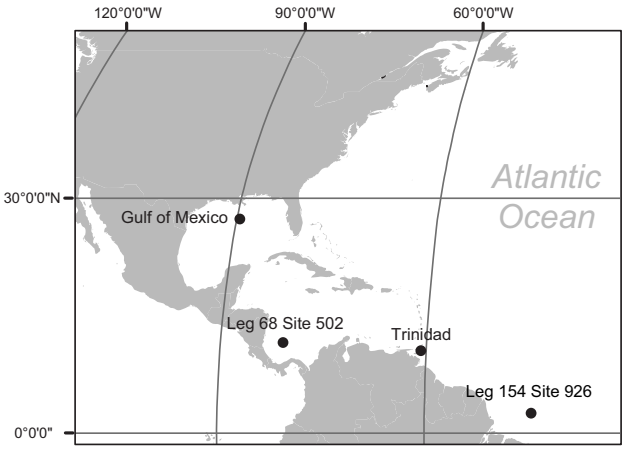

Figure 1: Locality map showing reference material for this study from Ceará Rise (ODP Leg 154, Site 926), the Gulf of Mexico, western Caribbean Sea (DSDP Leg 68, Site 502) and Bolli Collection, Trinidad

Samples were analyzed by multiple nannofossil paleontologists. Events were cross-checked and verified, and taxonomic concepts were synchronized, providing confidence in datum calibrations. All age calibrations are new and based on 14 years of analyses of the ODP Leg 154 materials. The backbone of the BP and Arco methodologies was the abundance cycle, while Amoco was strongly event-driven, the sequence of fossil tops taking precedence. The BP GNATTS (Bergen *et al*., in prep) is a hybrid of the methodologies and is based on a combination of tops, bases and abundance changes. The following stratigraphic abbreviations are used: LO (lowest occurrence) and HO (highest occurrence); abundance modifiers are R (regular) for LRO and HRO, F (few) for LFO and HFO, C (common) for LCO and HCO and Acme.

The objective of this work is to clarify taxonomic concepts and present the GoM stratigraphy developed over the past five decades from BP and its heritage companies, therefore this study does not compare our results to other published stratigraphies of the GoM Basin or research on ODP Leg 154 (*e.g.,* Denne, 2008; Raffi *et al*., 2016). The geologic ages derived from sampling of ODP Leg 154 are maintained at three decimal precision through the manuscript for consistency; errors stated on ages reflect the difference in age for the next sample analyzed upwards or downwards in the composite section. Nannofossil stratigraphic range charts are available from the PANGAEA web database (www.pangaea.de).

3. Biostratigraphy and taxonomy

In the Late Miocene, *Discoasters* provide key stratigraphic events for dividing the long Zone NN10. In the GoM, species of *Discoasters* have long been used for division of the Late Pliocene, and a discussion of the general groupings, taxonomic differentiations and biostratigraphic usage is provided for each group. Table 1 provides a summary of the main Late Miocene to Late Pliocene biostratigraphic events for species of *Discoaster* and *Minylitha* lineages as utilized by BP in the GoM. The stratigraphic use of species from these groups in the GoM and ODP Leg 154 is discussed from the Upper Pliocene NN19a (1.924Ma) through the Middle Miocene (17.692Ma) within NN3. The standard calcareous zonation (NP/NN Zones) of Martini (1971) is

Taxon	Event	Zone Martini (1971)	Age (Ma)	Hole-Core-Sec-Interval	Error (Ma)	Depth (rmcd)$_1$
Discoaster brouweri	HO	NN19A	1.924	926C-6H-5, 64–65cm	0.026	60.27
Discoaster triradiatus	HO	NN19A	1.924	926C-6H-5, 64–65cm	0.026	60.27
Discoaster dennei	HO	NN18	2.024	926B-7H-2, 35–36cm	0.021	62.97
Discoaster pentaradiatus	HO	NN17	2.327	926A-8H-3, 49–51cm	0.025	72.58
Discoaster surculus	HO	NN16	2.511	926C-8H-4, 21–22cm	0.012	78.23
Discoaster pliostellulus	HO	NN16	2.686	926A-9H-4, 19–20cm	0.027	84.73
Discoaster tamalis	HO	NN16	2.752	926C-9H-2, 73–75cm	0.023	86.70
Discoaster variabilis	HO	NN16	2.968	926C-9H-6, 80–82cm	0.022	92.77
Discoaster asymmetricus	INC	NN16	3.019	926A-10H-3, 64–66cm	0.026	94.15
Discoaster tamalis	INC	NN16	3.019	926A-10H-3, 64–66cm	0.026	94.15
Discoaster toralus	HO	NN15	4.085	926B-13H-2, 28–29cm	0.016	127.53
Discoaster pansus	HRO	NN15	4.244	926C-13H-3, 93–94cm	0.023	133.39
Discoaster neorectus	HRO	NN11b	6.445	926B-18H-4, 73–74cm	0.022	184.27
Discoaster subsurculus	HO	NN11b	6.457	926B-18H-4, 97–98cm	0.012	184.51
Discoaster pseudovariabilis	HRO/HO	NN11b	6.457	926B-18H-4, 97–98cm	0.012	184.51
Discoaster extensus	HO	NN11b	6.457	926B-18H-4, 97–98cm	0.012	184.51
Discoaster calcaris	HO	NN11b	6.801	926C-18H-7, 16–17cm	0.022	190.65
Discoaster loeblichii	HO	NN11b	6.821	926C-19H-1, 103–104cm	0.020	190.87
Discoaster icarus	HRO	NN11b	6.832	926C-19H-1, 121–122cm	0.011	191.05
Discoaster neohamatus	HO	NN11b	7.086	926B-19H-4, 91–92cm	0.021	195.25
Minylitha convallis	HO	NN11b	7.265	926B-19H-5, 124–125	0.010	197.08
Discoaster pachyloeblichii	HO	NN11b	7.332	926B-19H-6, 85–86cm	0.027	198.19
Discoaster breviloeblichii	HO	NN11b	7.374	926A-20H-2, 134–135cm	0.027	199.82
Minylitha convallis	INC/HRO	NN11a	7.848	926B-20H-5, 10–11cm	0.023	206.79
Discoaster prepent. prepentaradiatus	HO	NN10	8.449	926C-22H-3, 53–54cm	0.015	220.61
Discoaster loeblichii	LO	NN10	8.738	926B-22H-4, 95–96cm	0.024	224.81
Discoaster prepent. plautus	INC/HO	NN10	8.806	926B-22H-5, 49–50cm	0.021	225.85
Discoaster styzenii	HRO/HO	NN10	8.902	926B-22H-6, 25–27cm	0.011	227.12
Discoaster prepent. prepentaradiatus and Discoaster prepentaradiatus plautus	HCO	NN10	8.929	926A-23H-1, 3.5–5.5cm	0.013	227.61
Discoaster prepent. prepentaradiatus	LCO	NN10	9.095	926A-23H-2, 94.5–96.5cm	0.023	230.02
Discoaster bollii	HO	NN10	9.202	926A-23H-3, 115–117cm	0.018	231.72
Discoaster hamatus (<15)	HO	NN10	9.229	926A-23H-4, 20–22cm	0.018	232.27
Minylitha cancellata	HO	NN10	9.326	926A-23H-5, 1–3cm	0.025	233.58
Discoaster pentabollii	HO	NN10	9.377	926A-23H-5, 75.5–77.5cm	0.023	234.33
Discoaster hamatus (>15)	HO	NN9	9.451			
Discoaster caulifloris	HO	NN9	9.542	926A-23H-7, 17–19cm	0.037	236.74
Discoaster hamatus (>15)	HRO	NN9	9.618	926B-23H-5, 36–38cm	0.064	237.44
Discoaster tribollii	HO	NN9	9.618	926B-23H-5, 36–38cm	0.064	237.44
Discoaster bollii	2nd acme/INC	NN9	9.727	926A-24H-2,10–12cm	0.022	239.21
Discoaster hamatus (<15)	INC	NN9	9.727	926A-24H-2,10–12cm	0.022	239.21
Discoaster caulifloris	INC	NN9	9.781	926A-24H-2, 139–141cm	0.021	240.50
Discoaster gozoensis	HO	NN9	10.451	926A-25H-1, 72–74cm	0.030	249.08
Discoaster exilis	HO	NN9	10.490	926A-25H-1, 102–104	0.014	249.38
Discoaster bollii	LO	NN9	10.716	926A-25H-3, 47.5–49.5cm	0.016	251.84
Discoaster neohamatus	LO	NN9	10.800	926A-25H-3, 147–149cm	0.033	252.83
Discoaster hamatus (>15)	LO	NN9	10.963	926A-25H-5, 44–46cm	0.021	254.80
Discoaster hamatus (<15)	LO	NN8	11.509	926A-26H-2, 26.5–28.5cm	0.010	262.14
Discoaster exilis	LO	NN4	17.393	928B-28H-1, 25–26cm	0.014	272.89

Table 1: Main stratigraphic events for the Pliocene-Late Miocene *Discoaster* and *Minylitha* in the Gulf of Mexico
$_1$revised measured composite depth (meters); **bold = NN zonal marker**

widely used as a reference in the GoM, and taxonomic terminology follows Young *et al*. (1997).

The BP GNATTS is also correlated to the standard zonation of Martini (1971) and Okada & Bukry (1980) with some emendations (Blair *et al*., this volume; de Kaenel *et al.,* this volume), and is calibrated to the Astronomically Tuned Neogene Time Scale 2004 (ATNTS2004) (Lourens *et al*., 2004). This study uses the same section and material from which the ATNTS2004 and ATNTS2012 (Gradstein *et al*., 2012) was astronomically tuned to obtain well-calibrated age estimations of the calcareous nannofossil and foraminifera events.

The general groupings provided in this paper represent informal groupings necessary to provide organizational structure to this work only. These groups include: *Discoaster brouweri* Group (Plate 1, Figure 2); *Discoaster pentaradiatus - prepentaradiatus* Group (Plates 1, 2; Figure 3); *Discoaster surculus* Group (Plate 2); *Discoaster bollii* Group (Plate 3 and 5; Figure 4); *Discoaster hamatus* Group (Plate 4; Figure 3); *Discoaster loeblichii* Group (Plate 4; Figure 5); *Discoaster variabilis* Group (Plate 5; Figure 6); and *Minylitha convallis* Group (Plate 5).

4. Systematic paleontology

4.1 *Discoaster brouweri* Group (Plate 1; Figure 2)

This group includes simple forms that have long, narrow rays with simple tips and a small central area adorned with a small knob. All but one taxon in this group have rays that bend proximally (Figure 2). The *Discoaster brouweri* Group is fundamental to Upper Pliocene biostratigraphy in the GoM. We discuss six previously described species: *D. triradiatus, D. tamalis, D. blackstockae, D. asymmetricus, D. brouweri* and *D. neorectus,* and also describe one new taxon, *Discoaster dennei*. The extinction of *D. brouweri* marks the end of this lineage and the top of Zone NN18 globally. Below this extinction, the tops of *D. dennei*, *D. asymmetricus* and *D. tamalis* are utilized as important stratigraphic markers in Upper Pliocene Zones NN18–NN16.

Discoaster triradiatus Tan, 1927

Pl. 1, fig. 1

Remarks: *Discoaster triradiatus* has three strongly curved, bent rays and a small rounded knob.

Occurrence: In the GoM, the HO of *D. triradiatus* occurs at the same stratigraphic horizon marked by the HO of *D. brouweri*. This horizon is dated at 1.924Ma in Leg 154 and is coeval in the GoM (Table 1). *Discoaster triradiatus* ranges from the Upper Miocene (NN9) through terminal Pliocene (top NN18) in Leg 154 (Figure 2).

Discoaster tamalis Kamptner, 1967

Pl. 1, figs 2–4

1967 *Discoaster tamalis* Kamptner, p. 166, text-fig. 28

Remarks: Kamptner (1967) designated *D. tamalis* for asteroliths with four orthogonal, bent rays. The distal side was described as featureless and sutures are not visible; however, we have observed both features in well-preserved specimens. We have also observed specimens that are not orthogonal (Pl. 1, fig. 4).

Occurrence: All three heritage companies have utilized the HO of *D. tamalis* near the top of Zone NN16. This event is a coeval stratigraphic horizon in the GoM and Leg 154 and dated at 2.752Ma (Table 1). The LO of *D. tamalis* is coeval in the GoM and Leg 154 within Zone NN14 (Lower Pliocene) and dated at 4.666Ma (+\−0.022; 926B-14H-6, 30–31cm).

Discoaster blackstockae Bukry, 1973c

Pl. 1, fig. 5

1973 *Discoaster blackstockae* Bukry, p. 315, pl. 1, figs. 1–4

Remarks: Bukry (1973c) described *D. blackstockae* as a four-rayed species with tapering, non-bifurcate blade-like rays. The distinguishing feature of *D. blackstockae* is the oblong central area formed by the non–perpendicular intersection of rays, typically resulting in inter-ray angles of 60° and 120°. In comparison, the rays of *D. tamalis* are orthogonal to slightly asymmetrical.

Occurrence: We have not established a firm stratigraphic range for *D. blackstockae* in the GoM but provide a rough range of Upper Miocene to Pliocene. In Leg 154, the HO of *D. blackstockae* was observed within Zone NN18 and dated at 1.957Ma (+\−0.009; 926C-6H-6, 19–20cm); the LO is within Zone NN10 and dated at 8.891Ma (+\0.011; 926B-22H-6, 12–14cm).

Discoaster asymmetricus Gartner, 1969

Pl.1, figs 6–7

1969 *Discoaster asymmetricus* Gartner. p. 595, pl. 1, figs. 1–3

Remarks: Gartner (1969) described *D. asymmetricus* as a slender, five-rayed species of *Discoaster* distinguished by its ray asymmetry. The rays of these delicate forms "bend sharply proximally at their tip" like *D. brouweri* in form and may possess a small central knob; they are distinguished by their five rays and asymmetry (Figure 2). The main distinction between *D. asymmetricus* and *D. astellaris* is the characteristic plain central area of the later, for a detailed description see Blair *et al*. (2017) in this volume.

Occurrence: In the GoM, the HO of *D. asymmetricus* and *D. pliostellulus* (described herein) mark a stratigraphic horizon dated at 2.686Ma (Table 1). The first downhole increases in *D. asymmetricus* and *D. tamalis* mark a GoM stratigraphic horizon within Zone NN16 which is dated at 3.019Ma (Table 1). In Leg 154, the LO of *D. asymmetricus* was dated at 8.785Ma (+\−0.021; 926B-22H-5, 15–16cm), its HRO observed at 2.236Ma (+\−0.026; 926C-7H-5, 93–95cm) and its HO at 2.165Ma (+\−0.026; 926C-7H-3, 116–117cm).

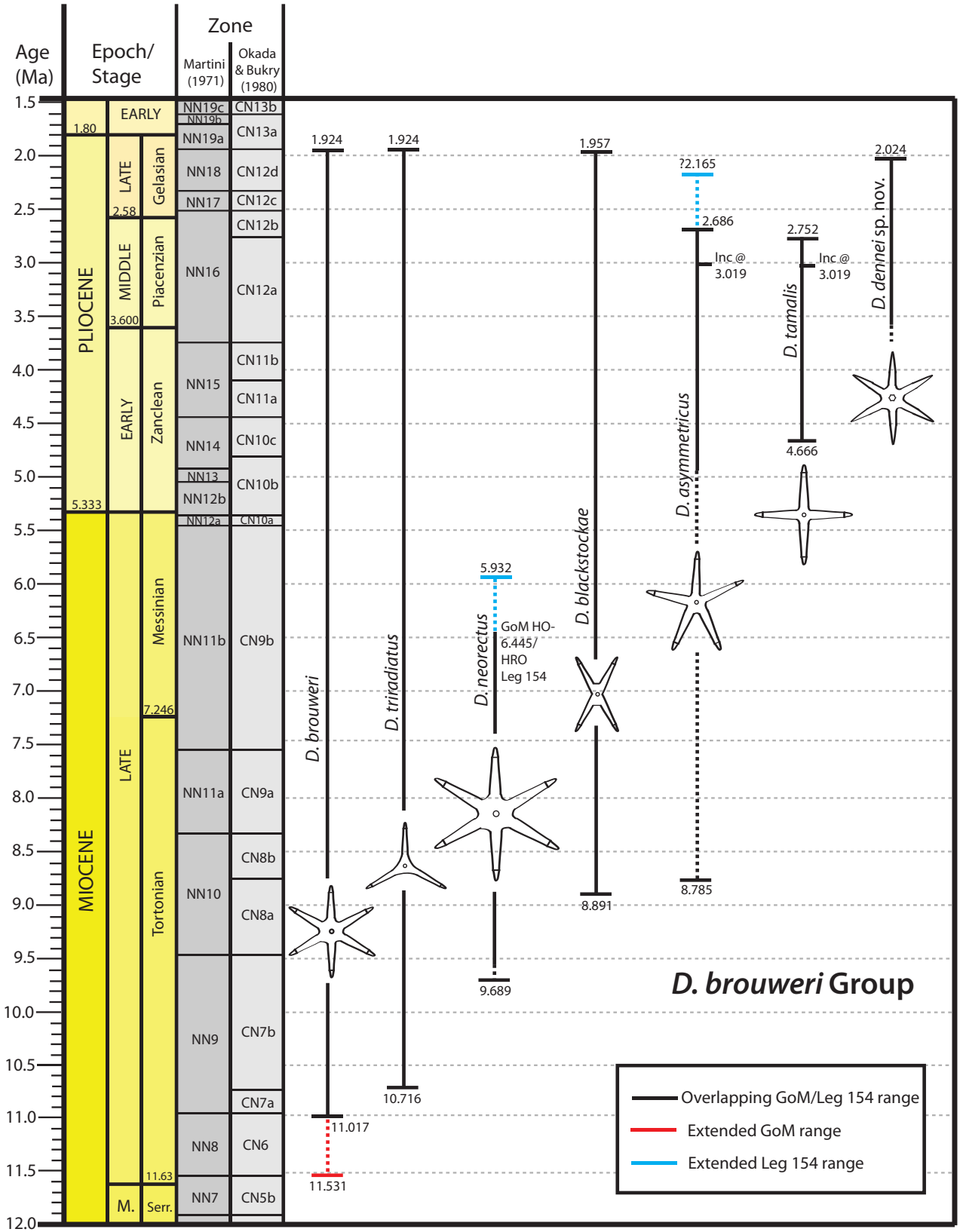

Figure 2: Range diagram of the *Discoaster brouweri* Group. Ranges, as well as new ages for the NN (Martini, 1971) and CN (Okada & Bukry, 1980) zonations, are derived from calibrated ages in ODP Leg 154 core samples as well as the Gulf of Mexico

***Discoaster brouweri* Tan, 1927, emend. Bramlette & Riedel, 1954**

Pl. 1, fig. 8

1927 *Discoaster brouweri* Tan (*pro parte*), p. 415, figs. 8a–b; *non* figs. 5–7, 14

1954 *Discoaster brouweri* Tan, 1927, emend. Bramlette & Riedel, p. 402, fig. 12; text-figs. 3a–b

Remarks: *Discoaster brouweri* is reserved for specimens with six bent rays. *Discoaster braarudii* and *D. dennei* (described below) are both constructed of six flat rays.

Occurrence: The HO of *D. brouweri* defines the top of Zone NN18 and is a coeval stratigraphic horizon in the GoM that has been utilized by all three heritage companies and dated at 1.924Ma in Leg 154 (Table 1). The LO of *D. brouweri* may have some stratigraphic utility in the GoM where it is observed ranging into the lower part of Zone NN8; just below the top of the newly described *Discoaster hexapleuros* (de Kaenel *et al*., this volume; 11.531Ma +\−0.011). In Leg 154, the LO was observed stratigraphically higher within Zone NN8 and dated at 11.017Ma (+\−0.009; 926A-25H-5, 106–108cm), just above the top of the newly described *Discoaster cuspidatus, D. emblematicus and D. ulnatus* (de Kaenel *et al*., this volume; 11.037Ma).

***Discoaster dennei* Browning & Bergen, sp. nov.**

Pl. 1, figs 9–11

Derivation of name: Named in honor of calcareous nannofossil specialist, Richard Denne, from Texas Christian University.

Diagnosis: A medium to large species of *Discoaster* with six straight, flat, tapering rays with pointed to slightly rounded ray terminations.

Description: Six-rayed *Discoaster* with long, straight, tapering rays and a small central area. A small knob is present on the proximal side. Holotype size = 12.4μm; Size = 8 to 15μm.

Remarks: *Discoaster dennei* was informally known as *Discoaster* "A" in the BP scheme. *Discoaster dennei* is distinguished from *D. brouweri* by its flat rays and *D. neorectus* by its smaller size. *Discoaster braarudi,* described by Bukry (1971b) from the Middle Miocene, has a very small central area and parallel-sided rays with blunt ray terminations.

Holotype: Pl. 1, fig. 9

Type Locality: ODP Leg 154, Hole 926C, Ceará Rise, western equatorial Atlantic

Type Level: Sample 926C-7H-6, 36–37cm (2.262Ma +\−0.024), Zone NN18, Upper Pliocene

Occurrence: The HO of *D. dennei* is coeval in the GoM and Leg 154 where it is dated at 2.024Ma within Zone NN18 (Table 1). The LO has not been tracked by BP or the heritage companies in the GoM, but in Leg 154 it is observed to range from the upper part of Zone NN11b.

***Discoaster neorectus* Bukry, 1971a**

Pl. 1, fig. 12

1971a *Discoaster neorectus* Bukry, p. 316, pl. 4, figs. 6–7

Remarks: Bukry (1971a) described *D. neorectus* as a "gigantic" 6-rayed species of *Discoasters* between 20–38μm across, with simple, sharp ray tips that lack downward extensions or bifurcations.

Occurrence: The HO of *D. neorectus* marks a prominent Upper Miocene (NN11b) GoM stratigraphic horizon in conjunction with the HOs of *Discoaster subsurculus* and HO (GoM)/HRO (Leg 154) of *Discoaster pseudovariabilis;* this horizon has been dated at 6.457Ma (Table 1). In Leg 154, the HRO of *D. neorectus* is observed slightly younger at 6.445Ma (Table 1). It should be noted that in Leg 154 spotty occurrences are observed younger to 5.932Ma (+\−0.028; 926B-17H-4, 127–128cm).

4.2 *Discoaster pentaradiatus - prepentaradiatus* Group (Plates 1, 2; Figure 3)

This group is characterized by five-rayed species of Discoasters with small central areas and long, tapering rays with broad bifurcations (Figure 3; Tan, 1927; Bramlette & Riedel, 1954). Speciation of this group is based on birefringence (Bukry & Percival, 1971), ray number (Wei, 2003; this study), and thickness of the broad bifurcations (Bukry & Percival, 1971; this study). Four described species and subspecies are discussed in this group: *D. pentaradiatus, D. styzenii, D. prepentaradiatus prepentaradiatus* and *D. extensus.* One new species is described, *D. trifolius,* as well as one new subspecies, *D. prepentaradiatus plautus. Discoaster extensus* has also been placed within this group for organizational purposes and because it is characterized by broad, symmetric, flaring bifurcations, like the group. The extinction of *D. pentaradiatus* at the top of Zone NN17 in the Upper Pliocene has long been a standard GoM marker. Extinctions of this group in the Late Miocene are useful in the GoM for the division of Zone NN10 (Figure 3; *D. styzenii, D. prepentpentaradiatus prepentaradiatus, D. prepentaradiatus plautus*).

***Discoaster pentaradiatus* Tan, 1927, emend. Bramlette & Riedel, 1954**

Pl. 1, fig. 27; Pl. 2, figs 1–2

1927 *Discoaster pentaradiatus* Tan, p. 416, fig. 14

1954 *Discoaster pentaradiatus* Tan, 1927, emend. Bramlette & Riedel, pp. 401–402, pl. 39, fig. 11; text-figs. 2a–b

Remarks: There is considerable variation in this species, including size, ray number, arm length and ray length. *Discoaster pentaradiatus* is distinguished from all other 5-rayed Neogene species of *Discoaster* by their faint birefringence in cross-polarized light and segmented nature. *Discoaster pentaradiatus* is further distinguished by its bifurcate rays.

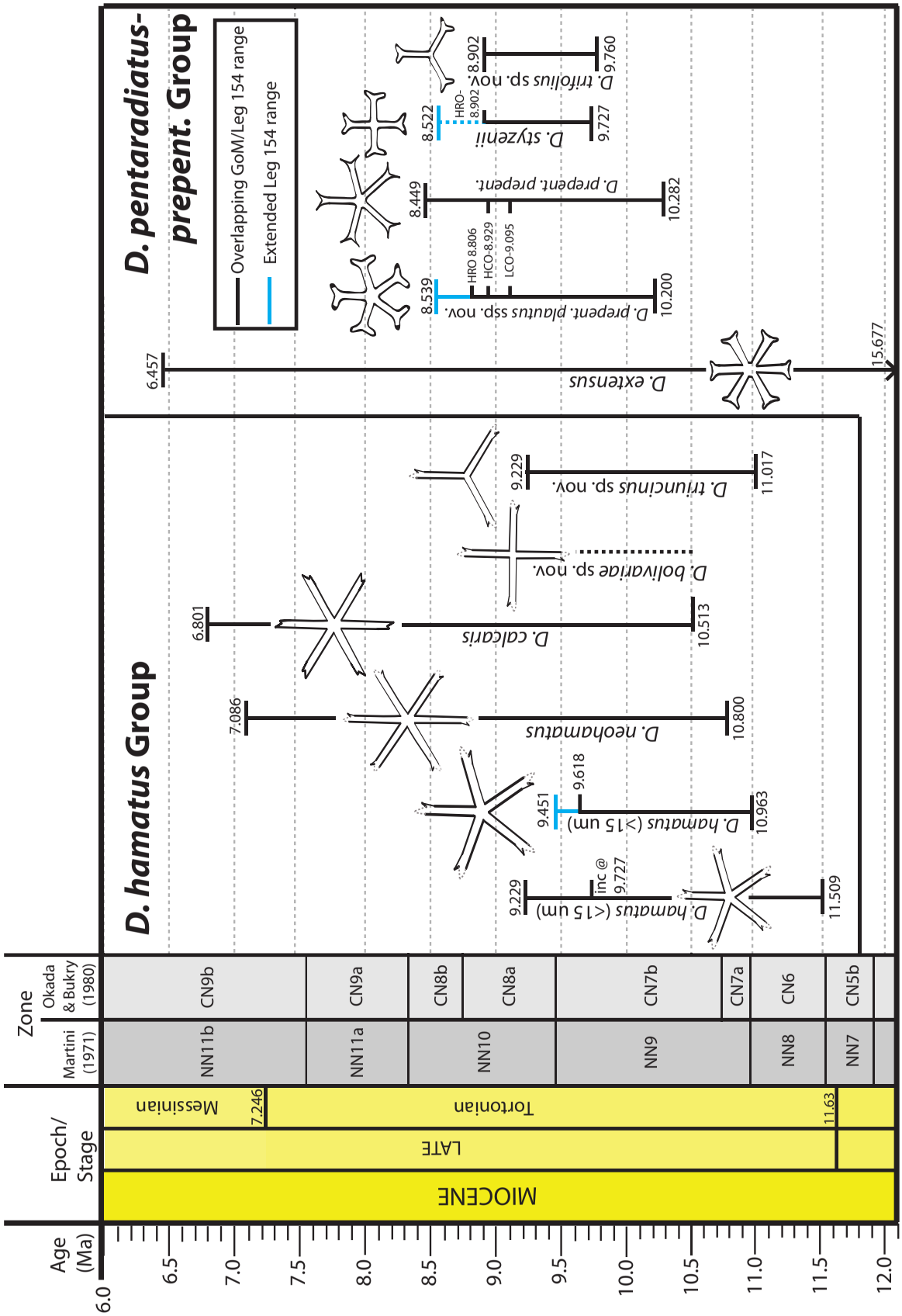

Figure 3: Range diagram of the *Discoaster hamatus* Group and *Discoaster pentaradiatus-prepentaradiatus* Group for the Late Miocene. Ranges, as well as new ages for the NN (Martini, 1971) and CN (Okada & Bukry, 1980) zonations, are derived from calibrated ages in ODP Leg 154 core samples as well as the Gulf of Mexico

Occurrence: The HO of *D. pentaradiatus* marks the top of Zone NN17 and has been utilized by all three heritage companies in the GoM for decades. This horizon is dated in Leg 154 at 2.327Ma (Table 1). Sporadic specimens, likely reworked, are observed higher in its stratigraphic range in Leg 154 up to 1.966Ma (+\−0.018; 926C-6H-4,130–131cm). The LO is observed within NN9 in the GoM and dated at 9.843Ma in Leg 154 (+\−0.011; 926A-24H-3,108–110cm), just below the HO (GoM)/ HRO (Leg 154) of *Catinaster coalitus* (de Kaenel *et al*., this volume; 9.826Ma).

Discoaster trifolius Browning & Bergen, sp. nov.

Pl. 1, fig. 13

Derivation of name: From the Latin *tri*, meaning three and *folius*, meaning leafy, leaved

Diagnosis: A three-rayed species of *Discoaster* having long, non-birefringent rays with symmetric bifurcations.

Description: A species of *Discoaster* having three long rays that are not birefringent. The rays broaden peripherally to form wide, delicate, symmetric bifurcations. A short distal knob is present in the small central area. Holotype = 10.0μm

Remarks: *Discoaster trifolius* is described for three-rayed *D. prepentaradiatus*. Other bifurcate three-rayed species of *Discoaster* are distinguished from *D. trifolius* in the following ways: *D. tribollii* has a high distal stem; *D. triuncinus* (described below) has asymmetric bifurcations, and three-rayed *D. pentaradiatus* are birefringent.

Holotype: Pl. 1, fig. 13

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

Type Level: Sample 926A-23H-4, 54.5–56.5cm (9.256Ma +\−0.023), Zone NN10, Upper Miocene

Occurrence: The HO of *D. trifolius* is coincident with the HRO (Leg 154)/HO (GoM) of *D. styzenii* in mid-NN10 and dated at 8.902Ma (+\−0.014; 926B-22H-6, 25–27cm) in Leg 154. The LO is in upper Zone NN9 and dated at 9.760Ma in Leg 154 (+\−0.021; 926A-24H-2, 91–93cm). The range of this species is not well established in the GoM.

Discoaster styzenii (Wei, 2003) Browning & Bergen, emend.

Pl. 1, figs 14–16

2003 *Discoaster styzenii* Wei, p. 21, pl. 2, figs. 5–8

Emended description: A species of *Discoaster* having four long rays that are not birefringent. The rays taper and then broaden peripherally to form symmetric bifurcations. The bifurcations are thin and broad. The angle formed by the rays is variable; they may be arranged in a symmetric or asymmetric fashion. A short distal knob is present in the small central area. Size range = 8.1–10.4μm (11 measured specimens)

Remarks: *Discoaster styzenii* is a four-rayed variant of *D. prepentaradiatus*. The short description of this species by Wei (2003) is insufficient to differentiate it from other four-rayed Neogene species of *Discoaster* with bifurcations. The emendation also includes specimens with orthogonal and symmetric rays. *Discoaster bolivariae* (described herein) has asymmetric bifurcations, and *D. quadribollii* (described herein) has a large and high distal stem. Four-rayed *D. variabilis* have thicker arms and bifurcations.

Occurrence: This species is found in deep-water GoM, and BP has long-utilized its extinction within Zone NN10 as a stratigraphic horizon. The HRO of *D. styzenii* is observed in mid-Zone NN10 and dated at 8.902Ma in Leg 154 (Table 1) and considered equivalent to the HO in the GoM. In Leg 154 younger, sporadic occurrences are observed to 8.522Ma (+\−0.017; 926C-22H-4, 7–8cm). The LO has not been established for this species in the GoM but was observed in ODP Leg 154 (upper Zone NN9) to range from 9.727Ma (+\−0.022; 926A-24H-2, 10–12cm).

Discoaster prepentaradiatus Bukry & Percival, 1971 *prepentaradiatus* Browning & Bergen ssp. nov.

Pl. 1, figs 23–26

1971 *Discoaster prepentaradiatus* Bukry & Percival (*pro parte*), p. 129, pl. 3, fig. 6; *non* fig. 7

Remarks: Bukry & Percival (1971) mentioned thin bifurcations in their description of this species. The bifurcations of the holotype are also delicate. It is likely that most of the delicate bifurcation is missing on the holotype. The species is further characterized by being planar and non-birefringent. The small central area has a small stellate knob, although no knob is mentioned in the description. Holotype = 10.5μm; Size = 9–20μm

Discoaster prepentaradiatus prepentaradiatus is differentiated from *D. pentaradiatus*, another five-rayed Neogene species of *Discoaster* with delicate bifurcations, as it is only faintly birefringent. *Discoaster prepentaradiatus plautus* (described below) has broad, thick bifurcations. *Discoaster hamatus* has asymmetric, curved bifurcations and significant size variation. Small specimens of *D. hamatus* are difficult to distinguish from small *D. prepentaradiatus prepentaradiatus* with the light microscope when the thin bifurcations of the latter are broken.

Occurrence: The HO of *D. prepentaradiatus prepentaradiatus*, the thin bifurcation variety, is dated at 8.449Ma in Leg 154 (Table 1) and represents the extinction of the entire *D. prepentaradiatus* group (3–5 rays) in the Upper Miocene uppermost Zone NN10 (Figure 3). The LO of the species is within Zone NN9 in the GoM and ODP Leg 154 and is dated at 10.282Ma (+/−0.014; 926A-24H-7, 11–13cm). The acme (HCO and LCO) of the species (both *D. prepentaradiatus prepentaradiatus* and *D. prepentaradiatus plautus;* described below) is not often observed in deep-water GoM wells because of a regional unconformity often associated with the HOs of *D. bollii* and *D. styzenii* (9.202Ma; Table 1). This acme lies in mid-Zone

NN10 within the Leg 154 section, spanning 9.095Ma (LCO *D. prepentaradiatus prepentaradiatus)* to 8.929Ma (HCO *D. prepentaradiatus prepentaradiatus*; Table 1).

Discoaster prepentaradiatus Bukry & Percival, 1971 *plautus* Browning & Bergen, ssp. nov.

Pl. 1, figs 17–19

1971 *Discoaster prepentaradiatus* Bukry & Percival (*pro parte*), p. 129, pl. 3, fig. 7; *non* fig. 6

Derivation of name: From the Latin *plautus*, meaning broad, flat

Diagnosis: A subspecies of *Discoaster prepentaradiatus* with thick, broad bifurcations

Description: A large species of *Discoaster* with five long, tapering rays and broad, thick bifurcations. The surface of the thick ray terminations appears "lipped," smooth and arcuate upon focus. Upon refocus, the juncture of the bifurcation appears notched. The rays are arranged symmetrically or asymmetrically; proximal ridges may run from the center down the median of the rays. The center is relatively large for the species, being about 1/4 to 1/5 the size of the specimen. A small central knob is present but may occupy up to 1.2 the size of the central area. Specimens are non-birefringent. Size = 10.4–12.5μm (six measured specimens)

Remarks: *Discoaster extensus* and *D. variabilis* have rare five-rayed variants that can be difficult to distinguish from *D. prepentaradiatus plautus*. In *D. extensus*, the rays are not thickened or "lipped" at their ends, although this surface is arcuate and has a distinct 'crescent moon'-like appearance. The ray terminations of *D. variabilis* do not have this smooth arcuate appearance but are notched. The generally smaller *D. prepent. prepentaradiatus* has narrow, thin bifurcations. The extinctions of the two subspecies of *D. prepentaradiatus* are stratigraphically close, but their stratigraphic separation has been utilized as distinct markers in GoM wells by BP for over a quarter century.

Holotype: Pl. 1, fig. 17

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

Type Level: Sample 926A-23H-2, 72.5–74.5cm (9.075Ma +/−0.020), Zone NN10, Upper Miocene

Occurrence: The HO of this subspecies is a marker in the GoM, and a coeval increase in ODP Leg 154 is dated at 8.806Ma (Table 1) and is slightly older than *Discoaster prepent. prepentaradiatus* (8.449Ma; Table 1). In Leg 154, the HO of *D. prepentaradiatus plautus* is observed younger at 8.539Ma (+/−0.019; 926C-22H-4, 38–39cm). The LO is observed within NN9 in Leg154 and dated at 10.200Ma (+/−0.034; 926A-24H-6, 66.5–68.5cm).

Discoaster extensus Hay, 1967

Pl. 1, figs 20–22

1967 *Discoaster extensus* Hay, in Hay, Mohler, Roth, Schmidt & Boudreaux; p. 451, pl. 3, figs. 10, 12, pl. 4, figs. 1–2

Remarks: The original description stresses the peripheral flare of the rays and bifurcations that curve sharply downward at the point of bifurcation. Upon focus, the bifurcations appear both notched at the level of the ray and arcuate at their tips, having a 'crescent-moon shape' appearance between the tips (Figure 3). Hay *et al.* (1967) also described rays of moderate length and breadth, a small central area (<1/2 the total diameter) lacking sculpture, and a size range of 11–13μm. The size range of this species is extended to 8–13μm, and very rare three to five-rayed forms have been observed. One specimen has rays whose length are about equal to the central area diameter (Pl. 1, fig. 20), whereas the remaining specimens all have rays that are at least 1.5 times longer the central area (Pl. 1, figs 21–22). A small central knob is present, and many specimens have medial ridges radiating from the center down the length of the rays. *Discoaster loeblichii* also has bifurcations that bend downward, but they bifurcate asymmetrically (Figure 5).

Occurrence: The HO of *D. extensus* marks a prominent Upper Miocene horizon (mid-Zone NN11b) in the GoM, along with the HOs of *D. neorectus*, *D. pseudovariabilis* and *D. subsurculus*. This horizon and the HO of *D. extensus* is dated at 6.457Ma (Table 1) in Leg154. The LO has not been used as a marker in the GoM but was observed in Leg154 to range into Zone NN4 and dated at 15.677Ma (+/−0.021; 925D-37H-2, 130–131cm).

4.3 *Discoaster surculus* Group (Plate 2)

The *Discoaster surculus* Group contains Late Pliocene to Late Miocene species of *Discoasters* with trifurcate bifurcations (Martini & Bramlette, 1963). Changes in the shape and orientation of the middle spur in the trifurcate bifurcation are used to distinguish species and subspecies of this group (Martini & Bramlette, 1963; Gartner, 1967; Martini & Worsley, 1971). The forms *D. toralus* and *D. pliostellulus* are included in this group for this paper, but they do not have trifurcate bifurcations and, instead, are characterized by rays with blunted ends. In the GoM, *D. subsurculus* and *D. pseudovariabilis* have extinctions at the same level within the Upper Miocene (Zone NN11b). Both species possess complex middle spurs. The last form in this group, *D. surculus*, has a simple, bright, bulb-shaped spur. Its extinction is a standard Upper Pliocene GoM marker and defines the top of Zone NN16. Four species are discussed from this group: *D. surculus, D. subsurculus*, *D. pseudovariabilis* and *D. toralus*. One new species is described, *D. pliostellulus*.

Discoaster surculus Martini & Bramlette, 1963

Pl. 2, figs 3–6, 8

1963 *Discoaster surculus* Martini & Bramlette, p. 854, pl. 104, figs. 10–12

Remarks: Martini & Bramlette (1963) reserved *D. surculus* for trifurcate species of *Discoasters* with simple, bright, bulb-shaped spurs and six or, rarely, fewer rays.

We have not observed any stratigraphic significance to the three- to five-rayed variants.

Occurrence: The HO of *D. surculus* marks the top of Zone NN16 and a coeval stratigraphic horizon in the GoM and Leg 154 utilized by all three heritage companies. In ODP Leg 154, the HO is dated at 2.511Ma (Table 1). The LRO of *D. surculus* is dated at 7.870Ma (+/−0.020; 926B-20H-5, 49–50cm) and LO is dated at 8.261Ma (+/−0.031; 926B-21H-5, 127–128cm) in Leg 154; neither has been used as a stratigraphic marker in the GoM.

***Discoaster subsurculus* Gartner, 1967**

Pl. 2, fig. 7

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

Remarks: *Discoaster subsurculus* has trifurcate ray terminations. The lateral branches of the trifurcation are broad; the protrusion between these branches is described as long and "knob-like" and often bends proximally. The proximal bend of the long central protrusion may have the appearance of a downward bending 'claw' in well-preserved specimens. *Discoaster subsurculus* is distinguished from the other two species with trifurcate rays, *D. surculus* and *D. pseudovariabilis*, by its long "knob-like" bending protrusion, where the central spur appears as a simple, bright, bulb-shaped spur in *D. surculus* and as "tongue-like," paired elements in *D. pseudovariabilis*.

Occurrence: The HO of *D. subsurculus* marks a prominent upper Miocene (NN11b) GoM stratigraphic horizon, along with the HOs of *D. pseudovariabilis* and *D. extensus*, and is dated at 6.457Ma in Leg 154 (Table 1).

***Discoaster pseudovariabilis* Martini & Worsley, 1971**

Pl. 2 figs 9–14

1971 *Discoaster pseudovariabilis* Martini & Worsley (*pro parte*), p. 1500, pl. 3, figs. 2–5; *non* pl. 3, figs. 6–8

Remarks: *Discoaster pseudovariabilis* has trifurcate ray terminations. Martini & Worsley (1971) described the radial portion of this trifurcation as a "tongue-like projection". *Discoaster surculus* and *D. subsurculus* are also trifurcate, but their radial projections are not "tongue-like" or composed of paired elements.

Occurrence: The HO of *D. pseudovariabilis* marks a prominent Upper Miocene (NN11b) GoM stratigraphic horizon along with the HOs of *D. subsurculus* and *D. extensus.* This horizon is dated at 6.457Ma in Leg 154 and represents the HRO of *D. pseudovariabilis* in Leg 154 (Table 1). Sporadic *s*pecimens of *D. pseudovariabilis* where observed stratigraphically younger in Leg 154 to 6.041Ma (+/−0.017; 926C-17H-4, 19–20cm).

***Discoaster toralus* Ellis, Lohman & Wray, 1972**

Pl. 2, figs 15–16

1972 *Discoaster toralus* Ellis, Lohman & Wray, p. 53, pl. 16, figs. 2–6

Remarks: *Discoaster toralus* has a relatively large central area and parallel-sided rays with flat to rounded terminations. It is characterized by the thick proximal ridges that radiate from the center down the rays and the inter-ray "webbing". *Discoaster intercalaris* and *D. pliostellulus* are other six-rayed forms with large, ornamented central areas, but their rays are tapered.

Occurrence: The HO of *D. toralus* is tied to a GoM stratigraphic horizon in zone NN15 marked by the HO of *Helicosphaera zeta* and dated in Leg 154 at 4.069Ma (Boesiger *et al*., 2017; this volume). In Leg 154 the HO of *D. toralus* was observed at 4.085Ma (+/−0.017; 926B-13H-2, 28–29cm).

Discoaster pliostellulus* Browning & Bergen, *sp. nov.

Pl. 2, figs 17–19

Derivation of name: From the Greek *pleion*, meaning more, and *stellula* (diminutive), meaning star

Diagnosis: A six-rayed species of *Discoaster* having short tapered rays

Description: An asterolith with a large central area and six, short tapering rays. The ray terminations are rounded, flat or slightly notched. Narrow, thick ridges extend from a prominent stellate central stem.

Remarks: *Discoaster pliostellulus* is described for Pliocene forms like the Miocene *D. stellulus*. In Leg 154, the ranges of these two species are separated by approximately 6My and *Discoaster toralus* ranges into the Lower Pliocene. It has thick radial ridges, but it differs from *D. pliostellulus* by having parallel-sided rays and inter-ray webbing.

Holotype: Pl. 2, fig. 19

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

Type Level: Sample 926-10H-2, 144–145cm (2.993Ma +\−0.026), Zone NN16, Middle Pliocene

Occurrence: The HO of *D. pliostellulus* is a long-standing BP GoM marker in the Middle Pliocene (uppermost Zone NN16) and dated at 2.686Ma Leg 154 (Table 1). In Leg 154, the LO is observed within the Lower Pliocene (lowermost Zone NN16) and dated at 3.707Ma (+/−0.020; 926A-12H-3, 73–74cm).

4.4 *Discoaster bollii* Group (Plates 3 and 5; Figure 4)

The *Discoaster bollii* Group is characterized by medium to large species of *Discoasters* with a thick, high knob in the central area and delicate bifurcations (Martini & Bramlette, 1963). The thick stem yields a 'shadow'- like, dark ring around the base of the stem. This group can be split into stratigraphically-useful taxa based on form and ray number (Wei, 2003; this study, Figure 4). Three of the species included in this group for this paper, *D. exilis*, *D. gozoensis* and *D. decorus*, do not have characteristics identical to those of the *Discoaster bollii* Group. These taxa possess delicate bifurcations like the group but do not

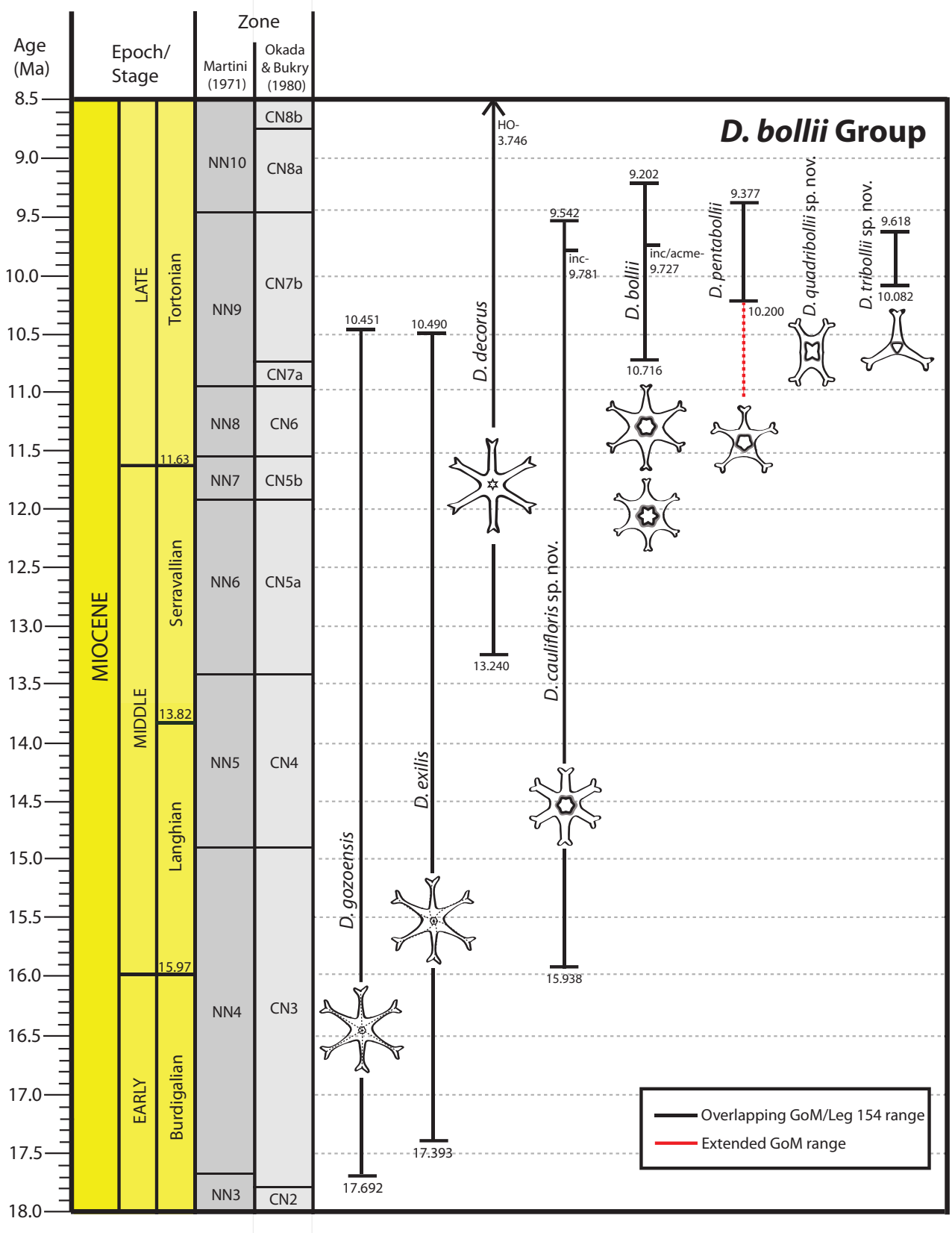

Figure 4: Range diagram of the *Discoaster bollii* Group for the Miocene. Ranges, as well as new ages for the NN (Martini, 1971) and CN (Okada & Bukry, 1980) zonations, are derived from calibrated ages in ODP Leg 154 core samples as well as the Gulf of Mexico

have a thick, high central knob. They are placed within this group for the convenience of this paper only because these taxa have delicate bifurcations like the group (Figure 4). The holotypes and taxa illustrated here were examined and photographed from material in the original Bolli collection (Bolli, 1957) sampled by H.M. Bolli in Trinidad. Five described taxa from this group are discussed: *D. bollii, D. pentabollii, D. exilis*, *D. gozoensis* and *D. decorus*. Three new species are described: *D. tribollii, D. quadribollii*, and *D. caulifloris.* The extinction of *D. bollii* has been long-used as GoM marker in the Upper Miocene Zone NN10. The use of the HO, acme or increase, and LO of this group provide stratigraphically useful events within Zones NN10 and NN9 in the GoM (Figure 4).

Discoaster bollii Martini & Bramlette, 1963

Pl. 3, figs 10–16

1963 *Discoaster bollii* Martini & Bramlette (*pro parte*), p. 851, pl. 105, fig. 1; *non* figs. 2–4, 7

Remarks: Martini & Bramlette (1963) described *D. bollii* as five-and-six rayed forms and illustrated specimens with varying arm lengths. The holotype has relatively long arms with a free ray length to center ratio of 0.71. We distinguish between forms with long (Plate 3, figures 10–13) and short arms (Plate 3, figures 14–16) but they do show identical ranges (Figure 4). The forms with short arms have a free ray length to central area ratios between 0.29 and 0.58. The original description is 10–14μm in size. This taxon is characterized on one side by a prominent large stellate stem with a height great enough as to appear in the light microscope as a bright central feature surrounded by a dark, 'shadow'- like ring at the base of the stem. The other side possesses a less prominent stem.

Occurrence: The extinction of *D. bollii* provides an important biostratigraphic event in the Upper Miocene (NN10), which has been used in the GoM for decades and is dated in Leg 154 at 9.202Ma (Table 1; Figure 4). The 2nd acme of *D. bollii*, along with the first increase of *D. hamatus* (<15), is used as a stratigraphic event within Zone NN9 in the GoM and is dated at Leg 154 as 9.727Ma (Table 1). This event in Leg 154 was observed as an increase in *D. bollii*, rather than an acme as observed in the GoM (Table 1). In the GoM, there is a smaller increase of *D. bollii* that is stratigraphically younger than the event represented by the dual increase in *D. bollii* and *D. hamatus* at 9.727Ma. The base of *D. bollii* has been observed as coeval in the GoM and Leg 154 within Zone NN9 and is dated at 10.716Ma in Leg 154 (Table 1).

Discoaster tribollii Browning & Bergen, sp. nov.

Pl. 3, figs 1–2

Derivation of name: From the Latin *tri,* meaning thrice and *bollii*, named in honor of Dr. Hans Bolli

Diagnosis: A *Discoaster* with three short, tapering rays with narrow bifurcations and a large stellate stem.

Description: A medium to large species of *Discoaster* with three long, tapering rays and short, narrow bifurcations. *Discoaster tribollii* is characterized by a large, stellate distal stem with a height great enough as to appear in the light microscope as bright central feature surrounded by a dark, 'shadow'- like ring at the base of the stem. The proximal side possesses a less prominent stem. Holotype = 8μm; the other specimen presented here is 11.4μm, assuming asymmetry.

Remarks: This taxon is distinguished from other three-rayed Neogene species of *Discoasters* by its high distal stem and delicate bifurcations. It is distinguished from other species of the *Discoaster bollii* group by its ray number.

Holotype: Pl. 3, fig. 1

Type Locality: Bolli Collection, Trinidad

Type Level: KR23425, Zone NN9, Upper Miocene

Occurrence: The HO of *D. tribollii* is near upper Zone NN9 in the GoM and Leg 154, where it was dated at 9.618Ma (Table 1). Its lowest occurrence in Leg 154 was observed in Zone NN9 (10.082Ma +/−0.028; 926A-24H-5, 107–109cm) but hasn't been well established in the GoM.

Discoaster quadribollii Browning & Bergen, sp. nov.

Pl. 3, figs 3–5

Derivation of name: From the Latin *quadri,* meaning four and *bollii*, named in honor of Dr. Hans Bolli

Diagnosis: A species of *Discoaster* that has four short, tapering rays with bifurcations and a large stellate stem.

Description: A medium to large *Discoaster* with four tapering rays with bifurcations. The rays may or may not be arranged orthogonally. The species is characterized by a large stellate stem with height great enough as to appear in the light microscope as bright central feature surrounded by a dark, 'shadow'- like ring at the base of the stem. The proximal side possesses a less prominent stem. Holotype = 10μm

Remarks: *Discoaster quadribollii* is distinguished from other four-rayed Neogene species of *Discoaster* by its high distal stem and bifurcations. It is distinguished from other species of the *Discoaster bollii* group by its four arms.

Holotype: Pl. 3, figs 3–5

Type Locality: Bolli Collection, Trinidad

Type Level: KR23425, *Globorotalia menardi* Zone, Zone NN9, Upper Miocene

Occurrence: The holotype for *D. quadribollii* was taken from lectotype material for *D. bollii* used by Martini & Bramlette (1963). We do not have a range for this taxon as it is extremely rare.

Discoaster pentabollii Wei, 2003

Pl. 3, figs 6–9

2003 *Discoaster pentabollii* Wei, p. 20 pl. 1, figs. 13–14

Remarks: Wei (2003) described this taxon as having five bifurcate rays with a large stellate stem and

relatively large central area. The two specimens illustrated by Wei (2003) have central areas approximately 1/3 the total size of the specimen. We have seen ratios of 1/4 to almost 1/2 of the total size of the specimen. We have also noticed the variation in the width of the stem, though all specimens have very high stems that appear to cast a shadow at the base of the stem, which is characteristic of the group. *Discoaster pentabollii* is distinguished from other species in the group by the number of rays. It also has tapering rays and short, narrow bifurcations. The size for specimens cited herein is 7.2–12.0μm.

Occurrence: In the GoM the HO of *D. pentabollii* is near the base of Zone NN10 and is dated in Leg 154 at 9.377Ma (Table 1). Its lowest occurrence in Leg 154 is in Zone NN9 (10.200Ma +/−0.034; 926A-24H-6, 66.5–68.5cm); however, its base is not well established in the GoM but has been observed into Zone NN8.

Discoaster caulifloris Browning & Bergen, sp. nov.

Pl. 3, figs 17–21

Derivation of name: From the Latin *cauli,* meaning stem and from L. *floris,* meaning blossom

Diagnosis: A species of *Discoaster* that has six long rays with wide bifurcations and a large stellate stem.

Description: A medium to large species of *Discoaster* with six long rays, which are parallel-sided to slightly tapering. The bifurcations are wide and broad, like those possessed by *D. variabilis*. The central area is approximately 1/3 the size of the specimen. The large stellate stem takes up approximately 1/2 of the central area with height great enough as to appear in the light microscope as bright central feature surrounded by a dark 'shadow'- like ring at the base of the stem. Size = 6–12.5μm

Remarks: *Discoaster caulifloris* is characterized by its wide bifurcations and roughly parallel-sided arms. In contrast, *D. bollii* has strongly tapering rays and delicate, narrow bifurcations.

Holotype: Pl. 3, fig. 20

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

Type Level: Sample 926A-24X-3, 108–110cm (9.843Ma +/−0.011), Zone NN9, Upper Miocene

Occurrence: The HO of *D caulifloris* is in Zone NN9 in the GoM and Leg 154, where it is dated at 9.542Ma (Table 1). Its lowest occurrence in Leg 154 ranges into Zone NN4 (15.938Ma +/−0.020; 925C-38H-3, 135–136cm). Its base is not well established in the GoM but is within the lower Middle Miocene. A stratigraphically useful increase in *D. caulifloris* is coeval in the GoM and Leg 154 and dated at 9.781Ma (Table 1).

Discoaster exilis Martini & Bramlette, 1963

Pl. 3, figs 22–26

1963 *Discoaster exilis* Martini & Bramlette, p. 852 pl. l04, figs. 1–3

Remarks: Martini & Bramlette (1963) described *D. exilis* as a six-rayed species of *Discoaster* with a small central area, small stellate knob and long, slender rays that taper outward. The distinguishing characteristic of *D. exilis* is the "faint ridges extending radially to one side of the median line" along the ray (Figure 4). These faint ridges extend from the center and curve along the side of the rays as clearly illustrated in the holotype (fig. 1). It is this curvature of the sutures down the side of the ray that distinguishes *D. exilis* from *D. gozoensis*, where the suture is linear and runs down the center of the rays (Figure 4). This very specific morphotypic distinction has long-been used by GoM workers and heritage companies. In the GoM, overgrowth can prevent preservation of this feature.

Occurrence: The HO of *D. exilis* is a key marker utilized by the three heritage companies in the GoM (lower Zone NN9) and has been dated in Leg 154 as 10.490Ma (Table 1). Its LO is a marker in the GoM and is observed slightly older than the LCO of *S. heteromorphus* (17.383Ma; Bergen *et al*., 2017; this volume) and dated in Leg 154 at 17.393Ma (Table 1; NN4).

Discoaster gozoensis Hojjatzadeh, 1978

Pl. 3, figs 27–30

1978 *Discoaster gozoensis* Hojjatzadeh, p. 10 pl. 3, figs. 2, 3

Remarks: The original description of *D. gozoensis* mentions ridges which radiate from the center along the median line of each ray, and originally illustrated specimens have six tapered rays with apparent narrow bifurcations (Hojjatzadeh, 1978). We separate *D. gozoensis* from *D. exilis* by the linear ridges that radiate down the median line of each ray (Figure 4), as opposed to their curved nature in *D. exilis*. In the BP nomenclature, this was previously referred to as *Discoaster* cf. *exilis.*

Occurrence: In the GoM, the HO of *D. gozoensis* is observed just above *D. exilis* in mid-Zone NN9 and dated in Leg 154 at 10.451Ma (Table 1). In the GoM, the LO is observed below the base of *D. exilis* (17.393Ma, Leg 154) in Zone NN3 and dated at 17.692Ma (+/−0.021; 928B-28-4, 135–136cm).

Discoaster decorus (Bukry, 1971b) Bukry, 1973b

Pl. 5, fig. 10

1971b *Discoaster variabilis decorus* Bukry, p. 48, pl. 3, figs. 5, 6

1973 *Discoaster decorus* (Bukry, 1971), p. 677, pl. 2, figs. 8, 9; pl. 4, fig. 11

Remarks: Bukryi (1971b) described this as a subspecies of *Discoaster variabilis*, distinguishing it by its narrow bifurcations and consistently larger size, giving a size range of 15–27μm. In addition, we distinguish *D. decorus* by both its large size and 'notches' in the narrow bifurcations.

Occurrence: In the GoM, the HO of *D. decorus* is loosely associated with the HO of *R. pseudoumbilicus*

(uppermost NN15), and both are dated at 3.746Ma in Leg 154 (+\−0.019; 926A-12-3, 134–135cm). Sporadic reworked specimens of *D. decorus* were observed stratigraphically younger in Leg 154 up to 3.531Ma (+/−0.012; 926C-11-3, 55–56cm).

4.5 *Discoaster hamatus* Group (Plate 4; Figure 3)

Martini & Bramlette (1963) originally described *D. hamatus* as forms with three to seven rays that are "long, somewhat curved, and turn sharply clockwise and downward toward at the end." In well-preserved specimens, the ray terminations have a distinguishable split in which one of the ray bifurcation turns downward. Next to this downward termination is a small, straight spur which leads to the split-nature of the asymmetric bifurcations (Figure 3). We restrict the name *D. hamatus* to forms with five rays and use *D. neohamatus* and *D. calcaris* for forms with six rays; two new species are described for three- and four-rayed variants, *D. triuncinus* and *D. bolivariae*, respectively. Two species in this group are emended, *D. hamatus* and *D. neohamatus*. The total range of *D. hamatus* (>15) defines Zone NN9 (Figure 3). In addition, small forms (less than 15μm) of *D. hamatus* have also been used by BP as a distinct stratigraphic event in the base of Zone NN10 in the GoM.

Discoaster triuncinus Browning & Bergen, sp. nov.

Pl. 4, figs 1–3

1984 *Eu-discoaster hamatus* (Martini & Bramlette) Theodoridis (*pro parte*), p. 174–175, pl. 37, fig. 7; *non*. pl. 12 fig. 13; *non.* pl. 37, figs. 4–6

Derivation of name: From the Latin *tri*, meaning three; and *uncinus*, meaning hook

Diagnosis: A three-rayed species of *Discoaste*r with long arms that sharply bend downward near their terminations with an accompanying small, straight spur.

Description: *Discoaster triuncinus* varies in size from approximately 8–12μm (measurements of three specimens). This taxon is the three-rayed variant of *D. hamatus*. Like *D. hamatus,* the long arms of this taxon bend sharply downward near the terminations at which point a small straight spur forms a small asymmetric bifurcation. Also, like *D. hamatus*, this straight spur is likely to be observed only in well-preserved specimens.

Remarks: The distinct downward bending bifurcations with accompanying spurs distinguish *D. triuncinus* from *D. trifolius*, which has delicate symmetric bifurcations, and from *D. tribollii*, which has a high stem and small equal bifurcations.

Holotype: Pl. 4, figs 1–2

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

Type Level: Sample 926A-24X-3, 20.5–22.5cm (9.803Ma +/−0.023), Zone NN9, Upper Miocene

Occurrence: There is uncertainty in the exact range because of its spotty and rare occurrences, but it has been observed from Zone NN8 (11.017Ma +/−0.009; 926A-25H-5, 106–108cm) - NN10 (9.229Ma +/−0.027; 926A-23H-4, 20–22cm) in Leg 154. In the GoM, the HO has been observed to be associated with the HO of *C. coalitus* (>10) and an increase in *C. coalitus* dated at 10.403Ma (+/−0.008; 926A-25H-1, 35–37cm) in Leg 154 (deKaenel *et al*., 2017; this volume).

Discoaster bolivariae Browning & Bergen, sp. nov.

Pl. 4, figs 4, 6

Derivation of name: Named in honor of foraminifera specialist, Maria Auxiliadora Bolivar from BP

Diagnosis: A four-rayed species of *Discoaster* that has long arms that sharply bend downward near their terminations with an accompanying small, straight spur.

Description: This is a four-rayed variant of *D. hamatus* and likewise has long arms and asymmetric bifurcations characterized by a sharp downward bend near the terminations with an accompanying small, straight spur. This taxon is medium to large in size; specimens range from 8–12μm and may have a small distal knob.

Remarks: *Discoaster bolivariae* is distinct from other four-rayed species of *Discoasters* by the nature of its ray terminations. It is distinguished from the other members of the *D. hamatus* group by its ray number.

Holotype: Pl. 4, fig. 6

Type Locality: Bolli Collection, Trinidad

Type Level: KR23425, Zone NN9, Upper Miocene

Occurrence: There is uncertainty in the range because of spotty and rare occurrences. The HO of *D. bolivariae* has been observed within Zone NN9 in Trinidad.

Discoaster hamatus (Martini & Bramlette, 1963) Browning & Bergen, emend.

Pl. 4, figs 5, 7–8, 10

1963 *Discoaster hamatus* Martini & Bramlette, p. 852–853, pl. 105, figs. 8,10,11

Emended Diagnosis: A five-rayed species of *Discoaster* with long arms that sharply bend downward near their terminations with an accompanying small, straight spur.

Remarks: This taxon is emended to restrict it to five-rayed forms. The original description mentioned a size range of 16–20μm. This criterion is critical because Zone NN9 is defined by the total range of *D. hamatus*. The authors have found its total range to be strongly size-dependent (Figure 3). We have chosen to use specimens of *D. hamatus* greater than 15μm to delineate the limits of Zone NN9. The smaller forms (less than 15μm) range stratigraphically higher and lower. These smaller forms of *D. hamatus* can also be difficult to distinguish between five-rayed forms of *D. prepentaradiatus* and *D. bellus* in poorly preserved materials where examination of ray terminations is difficult.

Occurrence: The HO and HRO of *D. hamatus* (>15) have been dated as 9.451Ma and 9.618Ma, respectively, in Leg 154. The HO in GoM calibrates to HRO in Leg 154 dated at 9.618Ma. The total range of *D. hamatus* (>15) is 10.963Ma to 9.451Ma (Table 1) and is used for the boundaries of Zone NN9 (Figure 3). The HO of the smaller variant of *D. hamatus* (<15) is dated in Leg 154 at 9.229Ma (Table 1). Isolated occurrences, likely reworked, have been noted in the Leg 154 material into Zone NN11b (7.402Ma +\−0.017; 926A-20H-3, 24–25cm). In the GoM, the LO of *D. hamatus* (<15), dated at 11.509Ma in Leg 154 (Table 1), is associated with the top of *D. kugleri* (deKaenel *et al*., 2017).

Discoaster neohamatus (Bukry & Bramlette, 1969) Browning & Bergen, emend.

Pl. 4, fig. 11

1969 *Discoaster neohamatus* Bukry & Bramlette, p. 133, pl. 1, figs. 4–5

Emended Diagnosis: A six-rayed species of *Discoaster* with long arms that are bent sharply downward near their terminations and have an accompanying small, straight spur.

Remarks: Bukry & Bramlette (1969) mentioned that *D. neohamatus* possesses six long slender rays which curve consistently in one direction and has no central area ornamentation. We believe the two specimens illustrated by Bukry & Bramlette (1969) are overgrown and have emended the description to include 1) that the ray ends possess two delicate bifurcations, in which one curves and bends in one direction with the other being a straight spur typical of the group; and 2) a central knob may be present. *Discoaster neohamatus* is often considered synonymous with *D. calcaris* (Gartner, 1967). Both species have asymmetric bifurcations, but in *D. calcaris* both bifurcations are relatively straight, the shorter only deviating slightly from ray axis. In *D. neohamatus* one of the bifurcations curves and the other is a straight spur characteristic of the *Discoaster hamatus* group (Figure 3). *Discoaster neohamatus* tends to have rays that are more delicate and thin than those of *D. calcaris*.

Occurrence: The range of *D. neohamatus* in the Leg 154 and GoM is Zones NN11b (7.086Ma) to NN9 (10.800Ma; Table 1).

Discoaster calcaris Gartner, 1967

Pl. 4, figs 9, 12

1967 *Discoaster calcaris* Gartner (*pro parte*), p. 2, pl. 2, figs. 1, 3a–b; *non* figs. 2a–b

Remarks: *Discoaster calcaris* has six long arms with narrow, asymmetric bifurcations. The longer limb of the bifurcation is straight (aligned with the ray). The shorter limb of the bifurcation is a spur that deviates slightly from the ray axis. In *D. neohamatus*, the longer limb of its asymmetric bifurcation curves and bends proximally, as is typical of the *D. hamatus* group (Figure 3). Gartner (1967) did not mention size in his description of *D. calcaris*, only highlighting that it is a very large species. The size range of specimens cited above and those illustrated herein is 13.6–20.8μm.

Occurrence: The HO of *D. calcaris* has a general association in the GoM with the stratigraphic horizon (Zone NN11b) marked by the HOs of *D. bergenii* and *D. loeblichii*. In Leg 154, this horizon and the HO of *D. calcaris* is dated at 6.801Ma (Table 1; Blair *et al*., 2017; this volume). The LO of *D. calcaris* is also well-constrained in both the GoM and Leg 154, occurring in both just below the HO of *D. exilis* (10.490Ma; Table 1), and dated at 10.513Ma (+\−0.045; 926A-25H-1, 123.5–125.5cm). Some GoM workers include *D. calcaris* within *D. neohamatus*, but *D. calcaris* has an older, Late Miocene extinction (Table 1).

4.6 *Discoaster loeblichii* Group (Plate 4; Figure 5)

The *Discoaster loeblichii* Group is characterized by six-rayed forms with unequal, asymmetric bifurcations that all bend in the same direction (Figure 5; Bukry, 1971b). Two new morphotypes of *D. loeblichii*, separated by their ray length and bifurcation thickness, are described here as new species, *D. breviloeblichii* and *D. pachyloeblichi*. GoM specimens in this group often possess broken rays and are poorly preserved; therefore, three full rays must be present to make a convincing identification. *Discoaster loeblichii* and its morphotypic splits provide stratigraphic events within the Upper Miocene (Zone NN11b) in the GoM (Figure 5).

Discoaster breviloeblichii Browning & Bergen, sp. nov.

Pl. 4, figs 18–21

Derivation of name: From the Latin *brevis*, meaning short, and *loeblichii*, after Alfred R. Loeblich Jr.

Diagnosis: *Discoaster* with a large center and six short rays that have asymmetric bifurcations

Description: Large asterolith measuring 8–10.8μm with six short, broad rays. The rays flare slightly towards the large center, whose diameter is about equal to the length of the rays. The rays flare peripherally to form unequal bifurcations that bend slightly out of the plane of the rays. The direction of the resulting asymmetric bifurcation is always the same for all rays. The central area is ornamented by six depressions around a small distal stem.

Remarks: *Discoaster breviloeblichii* is described for a short-rayed form of the *D. loeblichii* group and is the smallest of the three species. *Discoaster pachyloeblichii* has longer rays and thicker bifurcations (Figure 5). In the BP GoM lexicon, this was referred to as *D. loeblichii* "stubby".

Holotype: Pl. 4, fig. 18

Type Locality: DSDP Leg 68, Hole 502, Caribbean Sea

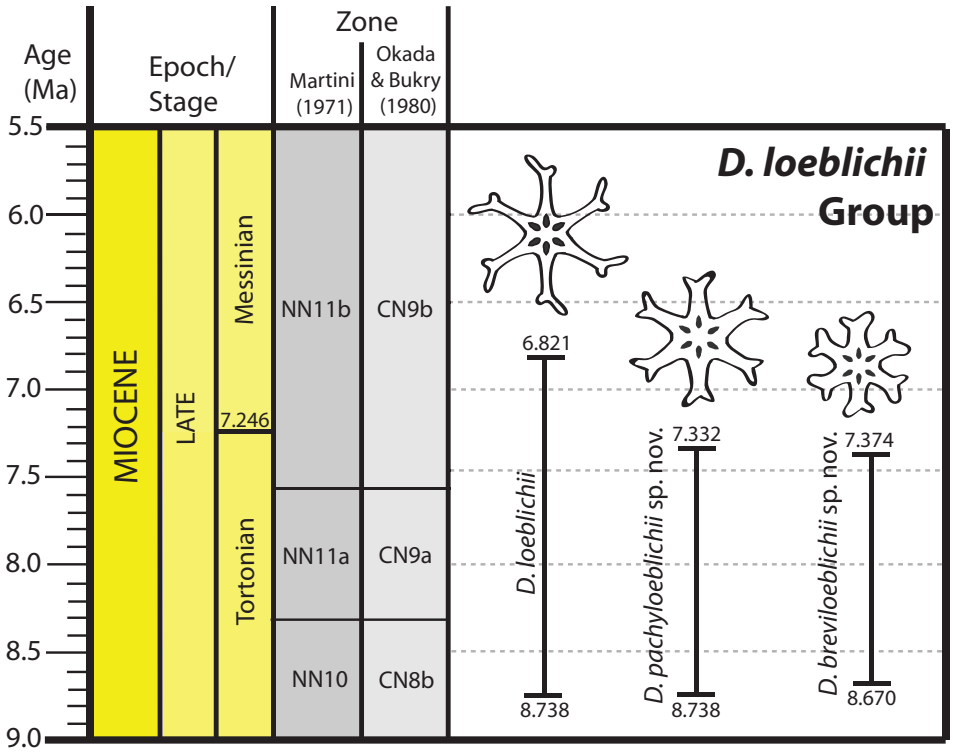

Figure 5: Range diagram of the *Discoaster loeblichii* Group for the late Miocene. Ranges, as well as new ages for the NN (Martini, 1971) and CN (Okada & Bukry, 1980) zonations, are derived from calibrated ages in ODP Leg 154 core samples as well as the Gulf of Mexico

Type Level: Sample 502-50-1, 19–20cm (209.89m), Subzone NN11a, Upper Miocene

Occurrence: The HO of *D. breviloeblichii* is observed just below that of *D. pachyloeblichii* in the BP GoM framework, as well as Leg 154, and is dated at 7.374Ma (Table 1). The LO was observed at 8.670Ma (+\−0.022; 926C-22H-5, 73–74cm) within NN10 at Leg 154.

Discoaster loeblichii Bukry, 1971a

Pl. 4, fig. 17

1971 *Discoaster loeblichii* Bukry; p. 315–316, pl. 4, figs. 3–5

Remarks: Bukry (1971a) described *D. loeblichii* as having "distinctive unequal bifurcations that are bent slightly out of the plane of the rays" and "sense of direction of the resulting asymmetric bifurcation is always the same for all six rays". In the GoM, recovered specimens are often missing rays and bifurcations, so at least three full rays with their bifurcations are needed to have any assurance of the direction. The ray bifurcations are diagnostic and shared with the two related new species described herein, which are differentiated either by ray length (*D. breviloeblichii*) or bifurcation thickness (*D. pachyloeblichii*). *Discoaster loeblichii* has long rays and thin (delicate) bifurcations (Figure 5). These three morphotypes are separated as species, and BP has long recognized their tops (extinctions) as different and stratigraphically useful in GoM wells. Bukry (1971a) gives a size range of 11–16μm for the species, although he described it as small to medium-sized.

Occurrence: The HO of *D. loeblichii* is a long-standing marker in the GoM, used by all three heritage companies. It has been associated in the GoM with the HOs of *D. bergenii* and *D. calcaris* in deep-water wells. This stratigraphic horizon and the HO of *D. loeblichii* has been dated at 6.821Ma in Leg 154 (Table 1; Blair *et al*., 2017; this volume). The LO of *D. loeblichii* is also well-constrained in the GoM and Leg 154, occurring just below the HO/INC of *D. prepentaradiatus plautus* (8.806Ma; Table 1). In Leg 154, *D. loeblichii* and *D. pachyloeblichii* have LOs at 8.738Ma (Table 1).

Discoaster pachyloeblichii Browning & Bergen, *sp. nov.*

Pl. 4, figs 13–16

Derivation of name: From the Greek *pachys*, meaning short, and *loeblichii*, after Alfred R. Loeblich Jr.

Diagnosis: *Discoaster* having six long rays with thick, asymmetric bifurcations that bend slightly out of the plane of the rays

Description: Large to very large asterolith with six long rays. The rays flare slightly towards the center, whose diameter is less than the length of the rays. The rays flare peripherally to form unequal bifurcations that bend slightly out of the plane of the rays. The direction of the resulting asymmetric bifurcation is always the same for all rays. The central area is ornamented by six depressions around a small distal stem. Size = 11.6–14.0μm (two specimens)

Remarks: *Discoaster pachyloeblichii* is distinguished from *D. loeblichii* by having thicker bifurcations. The two species are otherwise nearly identical. Although their taxonomic distinction is subtle, their stratigraphic tops are widely disparate in the GoM (estimated 420ky). *Discoaster breviloeblichii* is a smaller species having a larger center and shorter rays, but its stratigraphic range is nearly the same as *D. pachyloeblichii* (Figure 5). In the BP GoM lexicon, *D. pachyloeblichii* was referred to as *D. loeblichii* "thick".

Holotype: Pl. 4, fig. 16

Type Locality: DSDP Leg 68, Hole 502, Caribbean Sea.

Type Level: Sample 502-48-1, 90–91cm (201.80m), Subzone NN11a, Upper Miocene

Occurrence: The HO of *D. pachyloeblichii* is coeval in the BP GoM framework and Leg 154 and dated as 7.332Ma (Zone NN11b; Table 1). The LO of *D. pachyloeblichii* was dated in Leg 154 at 8.738Ma (+\−0.024; 926B-22H-4, 95–96cm).

4.7 *Discoaster variabilis* Group (Plate 5; Figure 6)

The *Discoaster variabilis* Group is characterized by large, 6-rayed species of *Discoasters* with broadly bifurcated rays. Martini & Bramlette (1963) originally used *D. variabilis* for all asteroliths with three to six rays. Specimens show bifurcate ray tips and a stellate central knob; however, several species within in this group can be distinguished based on the general width of the bifurcation angle, overall size and presence of a double bifurcation (Bukry & Percival, 1971; Bukry, 1973a,b; Stradner, 1973; this study, Figure 6). The extinctions of taxa within this group are stratigraphically useful in the GoM within the Pliocene Zones NN16 and NN15, and in the Upper Miocene Zone NN11b (Table 1; Figure 6). We discuss three described species from this group: *D. variabilis, D. pansus* and *D. icarus*. One new species is described, *Discoaster pansulus.*

Discoaster variabilis Martini & Bramlette, 1963

Pl. 5, figs 1–2

1963 *Discoaster variabilis* Martini & Bramlette (*pro parte*), p. 854, pl. 104, figs. 4–7; *non* figs. 8–9

Remarks: Martini & Bramlette (1963) described *D. variabilis* as asteroliths with three to six long rays with a stellate central knob and bifurcations. They also note proximal ridges along the median ray axes, but this is typical of many Neogene species of *Discoaster*. Martini & Bramlette (1963) also mentioned that some specimens may have double bifurcations; we now place these forms in *D. icarus*. Both *D. decorus* and *D. pansus* were originally described as subspecies of *D. variabilis*. *Discoaster decorus* has narrow bifurcations while *D. pansus* and *D. pansulus* have exceptionally wide bifurcations that nearly touch. *Discoaster variabilis* has bifurcations whose breadth is intermediate between these two species (Figure 6).

Occurrence: The HO of *D. variabilis* has long been utilized as a Pliocene GoM marker (mid-Zone NN16) by BP, and this stratigraphic horizon is dated as 2.968Ma (Leg 154; Table 1) where the planktonic foraminifera marker *Globorotalia multicamerata* is also used to define this stratigraphic horizon.

Discoaster pansulus Browning & Bergen, sp. nov.

Pl. 5, figs 3–5

Derivation of name: From the Latin *pansulus* (diminutive), meaning spread, stretch, extend

Diagnosis: An asterolith measuring less than 15μm with six long rays that flare to form very broad bifurcations nearly perpendicular to the rays.

Description: Medium to very large asterolith with six long rays. The rays flare peripherally to form very broad, symmetric bifurcations that are almost perpendicular to the rays. The center is small to medium-sized, and a small central stem is present. In some specimens, ridges radiate down the median of the rays. Specimens measured are less than 15μm; Size = 10.0–14.0μm (five measured specimens).

Remarks: *Discoaster pansulus* is described for specimens less than 15μm, previously referred to as *Discoaster* cf. *pansus* within BP GoM. *Discoaster pansus* is reserved for specimens larger than 15μm.

Holotype: Pl. 5, fig. 4

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

Type Level: Sample 926A-23-5, 1–3cm, (9.326Ma +\−0.028) Zone NN10, Upper Miocene

Occurrence: The HO *D. pansulus* in Zone NN15 is dated at 4.032Ma (+/−0.016; 926C-12H-6, 42–43cm) in Leg 154.

Discoaster pansus (Bukry & Percival, 1971) Bukry, 1973b

Pl. 5, figs 6–7

1971 *Discoaster variabilis pansus* Bukry & Percival, p. 129, pl. 3, figs. 8–9

1973 *Discoaster pansus* (Bukry & Percival) Bukry, p. 678, pl. 4, fig. 25

Remarks: Bukry & Percival (1971) characterized *D. pansus* as a large, six-rayed species of *Discoaster* with broadly bifurcated tips that are nearly perpendicular to the rays. They remarked that *D. decorus* differed in having very narrow, small bifurcations and *D. variabilis* in having moderately-sized and angled bifurcations intermediate between the other two species. Bukry & Percival (1971) gave a size range of 15–25μm for the species; smaller specimens between 15.4–15.8μm are illustrated herein (Plate 5). *Discoaster pansulus* is reserved for specimens <15μm and *D. pansus* for those >15μm.

Occurrence: The HRO of *D. pansus* is a long-utilized BP GoM marker and dated at 4.244 in Leg 154 (Table 1).

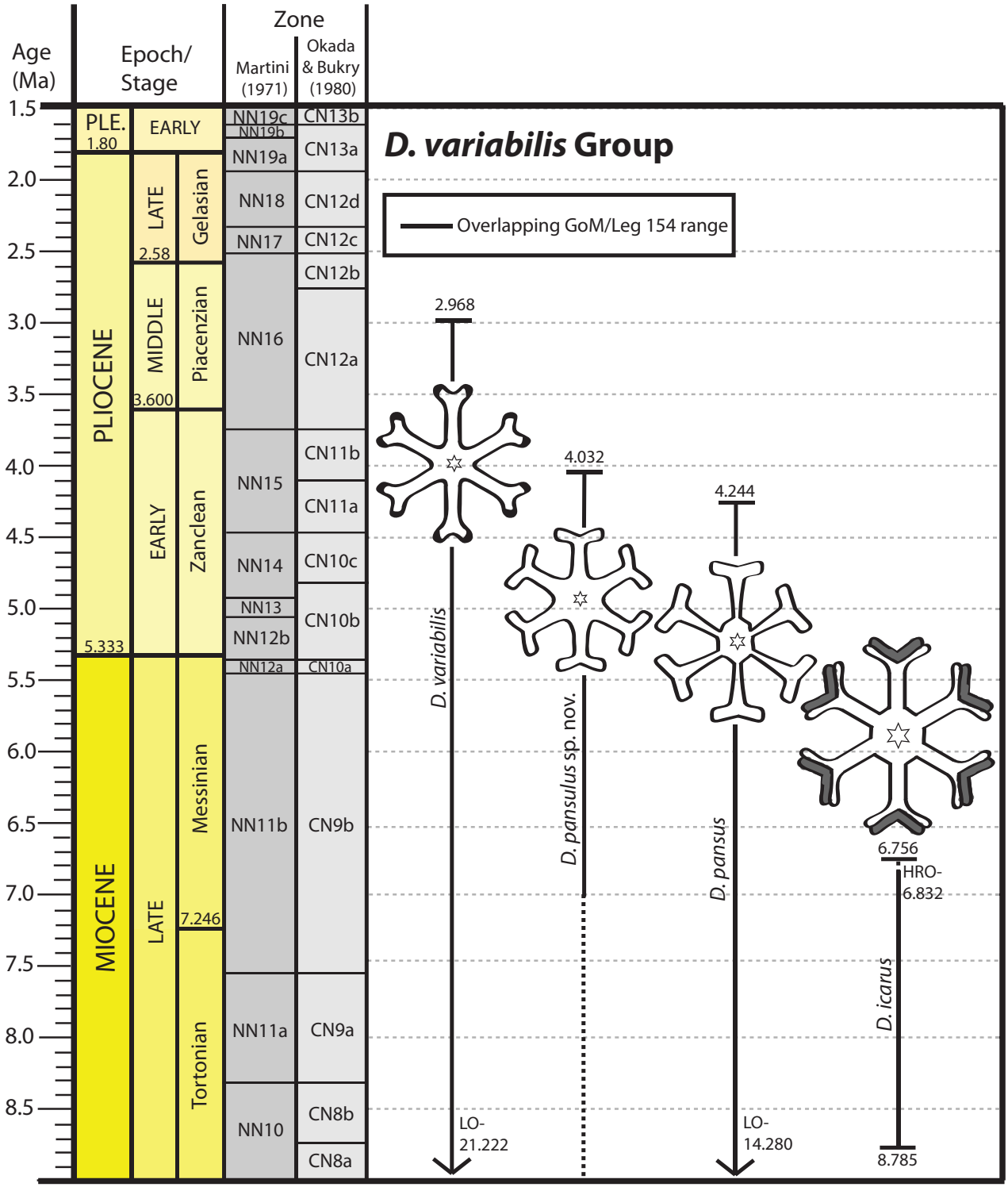

Figure 6: Range diagram of the *Discoaster variabilis* Group. Ranges, as well as new ages for the NN (Martini, 1971) and CN (Okada & Bukry, 1980) zonations, are derived from calibrated ages in ODP Leg 154 core samples as well as the Gulf of Mexico

***Discoaster icarus* (Stradner, 1973)**

Pl. 5, figs 8–9

1963 *Discoaster variabilis* Martini & Bramlette (*pro parte*), p. 854, pl. 104, fig. 8; *non* figs. 4–7, 9

1973 *Discoaster icarus* Stradner, p. 1138, pl. 41, figs. 7, 10–11; pl. 42, figs. 1–6, 9, 10

Remarks: Stradner (1973) diagnosed *D. icarus* as "a species of *Discoaster* of the *D. variabilis* group with rays terminating in a wide-angle of bifurcation of branches with 'flaps' between the branches" (Figure 6). These "flaps" are the "double bifurcations in some specimens" mentioned in the description of *D. variabilis* by Martini & Bramlette

(1963). Stradner (1973) mentioned a size of 30μm and smaller but illustrated nine specimens by light photomicrograph with a size range between 10.7–24.1μm. *Discoaster icarus* was not subdivided into size categories in our Leg 154 research.

Occurrence: The HRO of *D. icarus* has long-been utilized as an Upper Miocene GoM marker by BP and referred to as *D. cf. icarus* (small) and has been dated in Leg 154 at 6.832Ma (Table 1). The HO of *D. icarus* was observed at 6.756Ma in Leg 154 (+/−0.023; 926C-18-6, 91–92cm).

4.8 *Minylitha convallis* Group (Plate 5)

The *Minylitha* Group is characterized by birefringent T- and I-shaped bars in side view position that appear as kite-shaped wedges in the basal position (Bukry, 1972; Theodoridis, 1984). The HO and HRO of *M. convallis* are important GoM heritage markers in Upper Miocene Zone NN11a. This group includes one well-established species, *M. convallis,* and a new species described here, *M. cancellata.*

Minylitha convallis Bukry, 1973b emend. Theodoridis, 1984

Pl. 5, figs 11–13

1973b *Minylitha convallis* Bukry, p. 679, pl. 3, figs. 12–18
1984 *Minylitha convallis* Bukry, Theodoridis, p. 84, pl. 4, figs. 1–7

Remarks: *Minylitha convallis* has T-shaped or I-shaped cross sections that display a bright, 1st order white birefringence; in the distal position the kite-shaped wedges are mostly dark in cross-polarized light except for their faintly birefringent outline.

Occurrence: The HO of *M. convallis* is coeval in the GoM and Leg 154, where it has been dated at 7.265Ma (Table 1). The HRO of *M. convallis*, paired with the HO of *Helicosphaera orientalis* in the GoM framework, is associated with its first downhole increase of *M. convallis* in the Leg 154 section and dated at 7.848Ma in Zone NN11a (Table 1; Boesiger *et al*., 2017; this volume). The LO of *M. convallis* is dated at 9.749Ma (+\−0.011; 926A-24-2, 61–63cm).

Minylitha cancellata Browning & Bergen, *sp. nov.*

Pl. 5, figs 14–22

Derivation of name: From the Latin *cancellatus*, meaning latticed, cross-barred, grilled

Diagnosis: *Minylitha* with a thickened longitudinal ridge(s) and multiple, parallel, transverse ridges

Description: A small triangular to sub-pentagonal nannolith. A prominent longitudinal ridge or paired ridges run the length of the nannolith and are more birefringent (1st order white) than the rest of the nannolith. Three to five parallel transverse ridges radiate from either side of the longitudinal ridge(s) giving the impression of a canceollate pattern. Forms observed have a Y-shaped cross-section with the longitudinal ridge forming the base of the "Y" (Pl. 5, figs 17–18). Length to width ratios are roughly 0.85–1.17 (10 specimens). Size = 3.2–5.6μm

Remarks: *Minylitha convallis* has either a T-shaped or I-shaped cross section, as opposed to the Y-shaped cross-section of *M. cancellata*. Both species are made of triangular wedges, but *M. cancellata* is distinguished by its series of transverse ridges. In overgrown specimens, the transverse ridge may appear as one solid ridge.

Holotype: Pl. 5, figs 15–16

Type Locality: Bolli Collection, Trinidad

Type Level: KR23425, *Globorotalia menardi* Zone, NN9, Upper Miocene

Occurrence: *Minylitha cancellata* is restricted to the Upper Miocene (NN9–NN10); the stratigraphic range is coeval in the GoM and Leg 154. Its range is dated from 10.122 (+\−0.023; 926A-24-5, 146.5–148.5cm) to 9.326Ma (Table 1) in Leg 154.

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Finally, it has not been lost on the authors that these five papers introduce a beastly barrage of brand-new bugs, their authors beginning with B. Not since Wind & Wise *in* Wise & Wind (1977) has this had the potential for confusion. From Blair, Bergen, Browning and Boesiger… we apologize, briefly.

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Plate 1

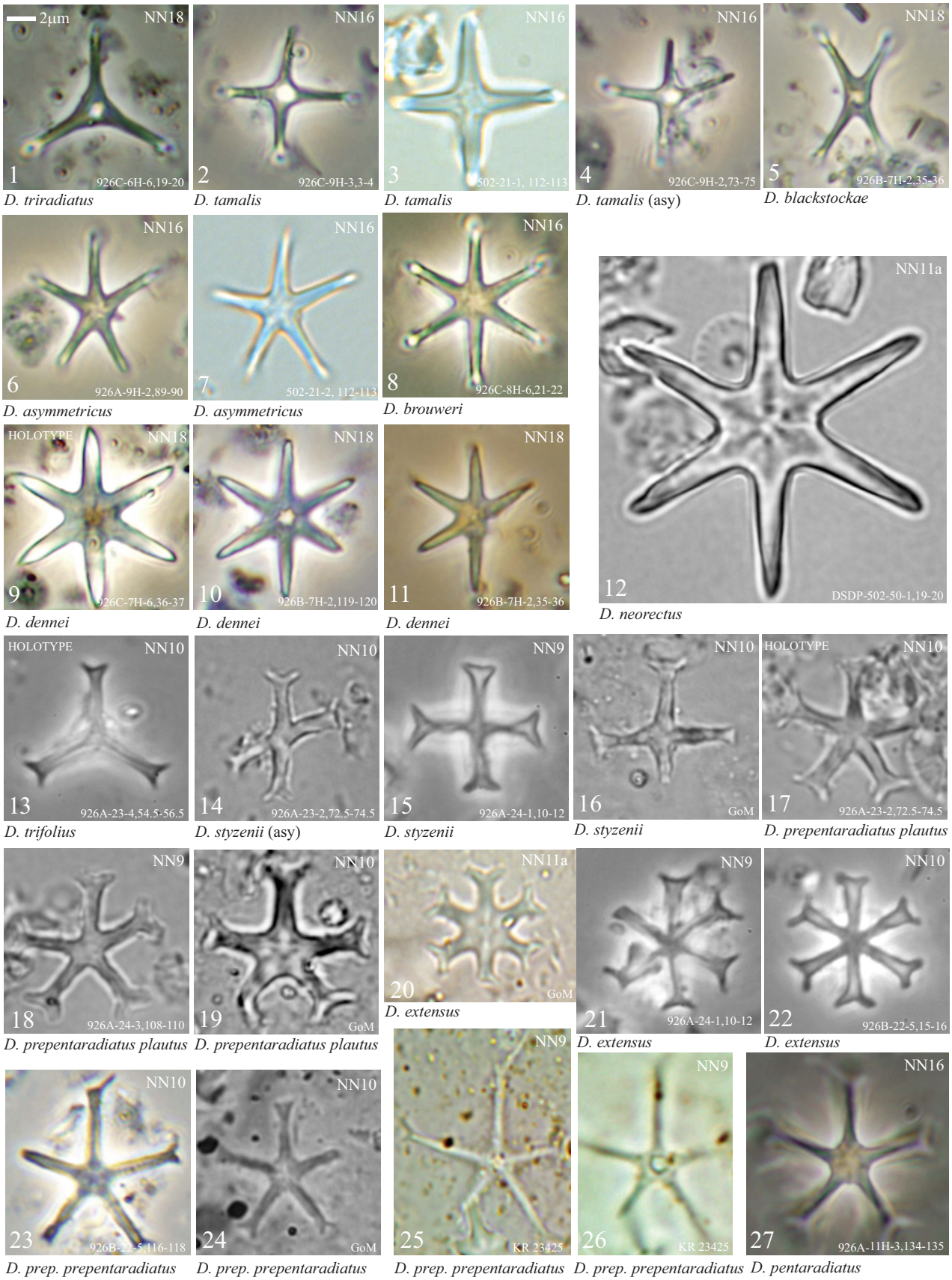
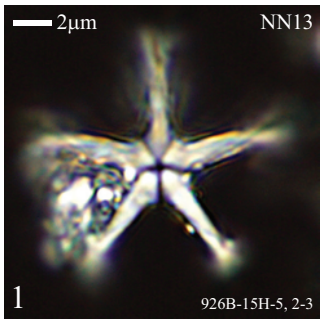
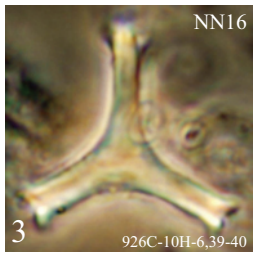

2µm
NN18
1
926C-6H-6,19-20
D. triradiatus
NN16
2
926C-9H-3,3-4
D. tamalis
NN16
3
502-21-1, 112-113
D. tamalis
NN16
4
926C-9H-2,73-75
D. tamalis (asy)
NN18
5
926B-7H-2,35-36
D. blackstockae
NN16
6
926A-9H-2,89-90
D. asymmetricus
NN16
7
502-21-2, 112-113
D. asymmetricus
NN16
8
926C-8H-6,21-22
D. brouweri
NN11a
12
DSDP-502-50-1,19-20
D. neorectus
HOLOTYPE
NN18
9
926C-7H-6,36-37
D. dennei
NN18
10
926B-7H-2,119-120
D. dennei
NN18
11
926B-7H-2,35-36
D. dennei
HOLOTYPE
NN10
13
926A-23-4,54.5-56.5
D. trifolius
NN10
14
926A-23-2,72.5-74.5
D. styzenii (asy)
NN9
15
926A-24-1,10-12
D. styzenii
NN10
16
GoM
D. styzenii
HOLOTYPE
NN10
17
926A-23-2,72.5-74.5
D. prepentaradiatus plautus
NN9
18
926A-24-3,108-110
D. prepentaradiatus plautus
NN10
19
GoM
D. prepentaradiatus plautus
NN11a
20
GoM
D. extensus
NN9
21
926A-24-1,10-12
D. extensus
NN10
22
926B-22-5,15-16
D. extensus
NN10
23
926B-22-5,116-118
D. prep. prepentaradiatus
NN10
24
GoM
D. prep. prepentaradiatus
NN9
25
KR 23425
D. prep. prepentaradiatus
NN9
26
KR 23425
D. prep. prepentaradiatus
NN16
27
926A-11H-3,134-135
D. pentaradiatus

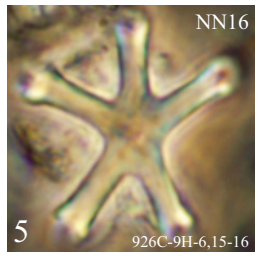
Plate 2



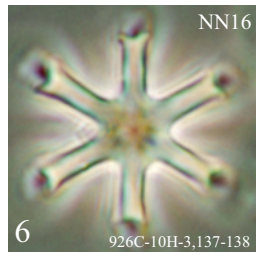


D. surculus (3ray)

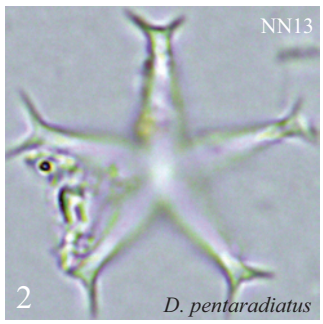
D. surculus (4ray)

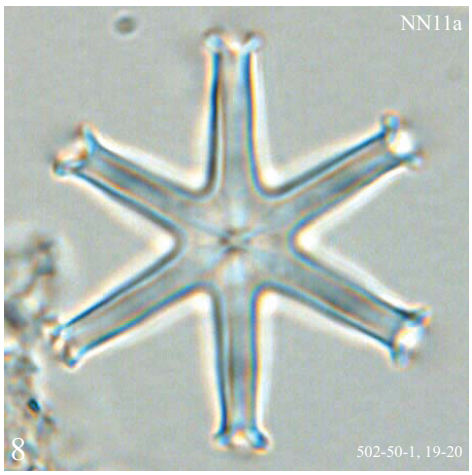


D. surculus (5ray)



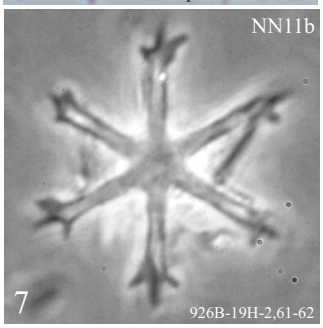
D. surculus



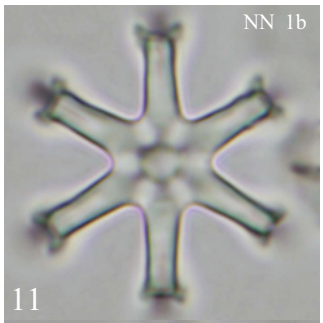


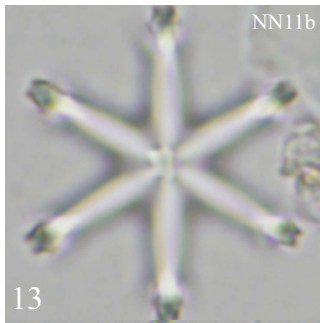
D. surculus

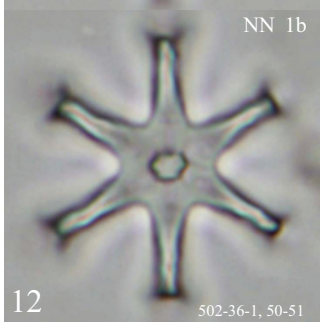
D. pseudovariabilis

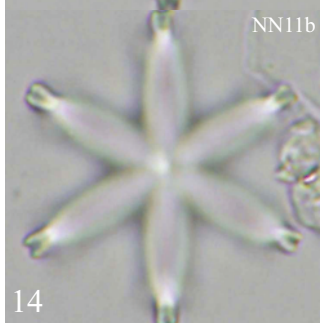


D. subsurculus

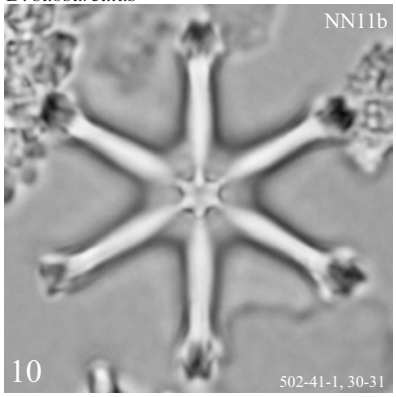




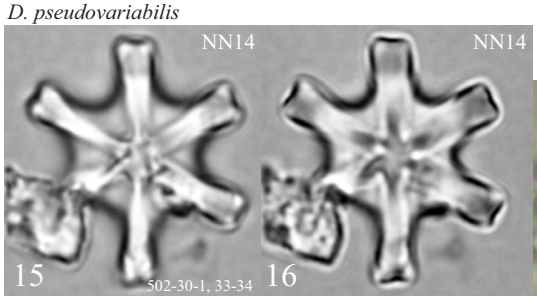




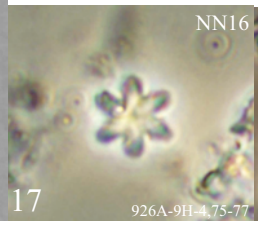
D. pseudovariabilis



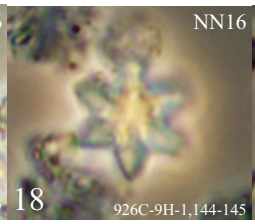
D. pseudovariabilis



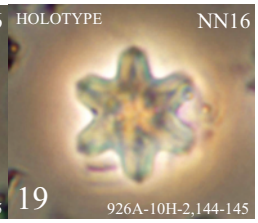
D. toralus



D. pliostellulus



D. pliostellulus



D. pliostellulus

Plate 3

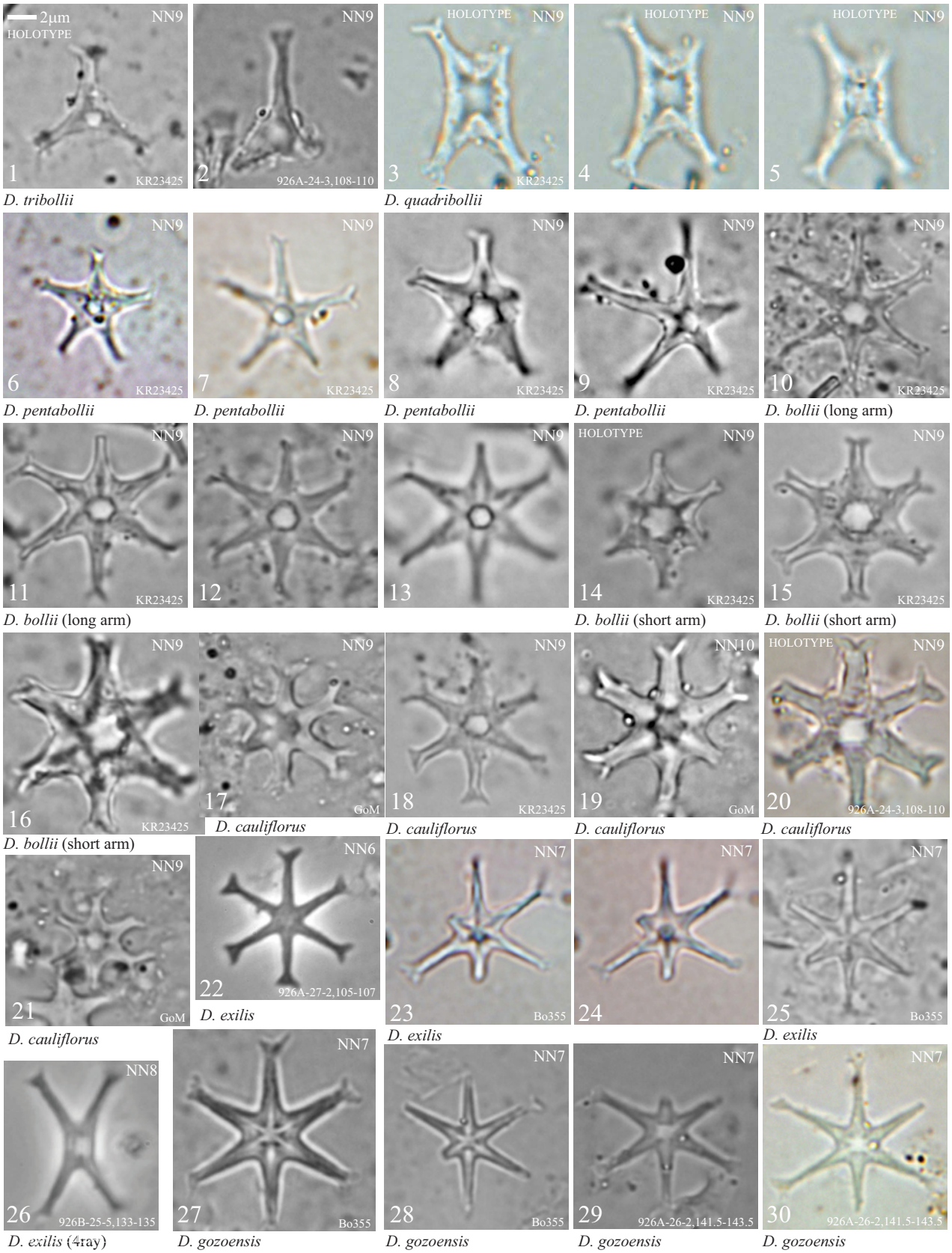

2µm
HOLOTYPE
NN9
1 KR23425
D. tribollii
2 926A-24-3,108-110
3 KR23425
D. quadribollii
4
5
6 KR23425
D. pentabollii
7 KR23425
D. pentabollii
8 KR23425
D. pentabollii
9 KR23425
D. pentabollii
10 KR23425
D. bollii (long arm)
11 KR23425
D. bollii (long arm)
12
13
14 KR23425
D. bollii (short arm)
15 KR23425
D. bollii (short arm)
16 KR23425
D. bollii (short arm)
17 GoM
D. cauliflorus
18 KR23425
D. cauliflorus
NN10
19 GoM
D. cauliflorus
20 926A-24-3,108-110
D. cauliflorus
21 GoM
D. cauliflorus
NN6
22 926A-27-2,105-107
D. exilis
NN7
23 Bo355
D. exilis
24
25 Bo355
D. exilis
NN8
26 926B-25-5,133-135
D. exilis (4ray)
27 Bo355
D. gozoensis
28 Bo355
D. gozoensis
29 926A-26-2,141.5-143.5
D. gozoensis
30 926A-26-2,141.5-143.5
D. gozoensis

Plate 4

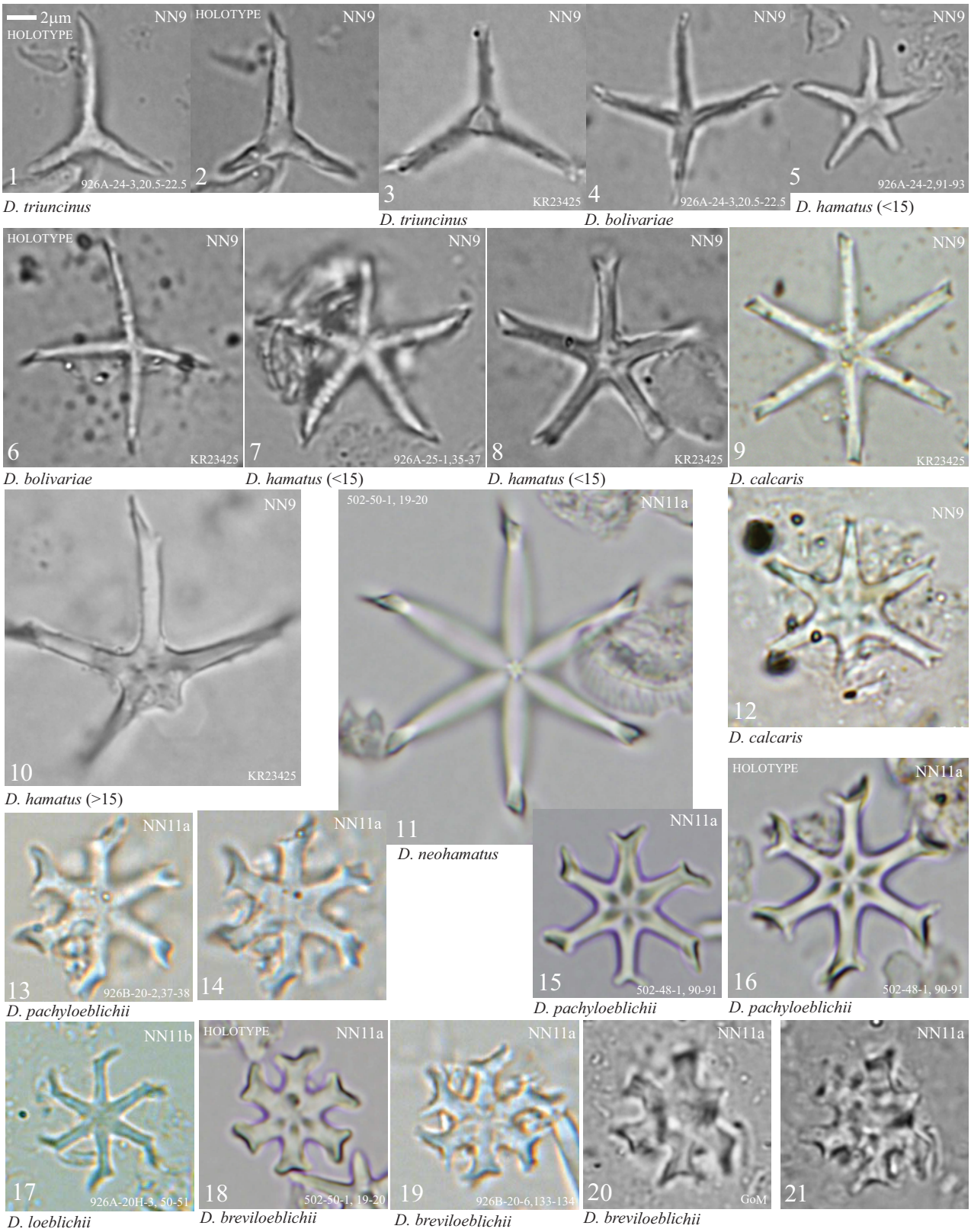
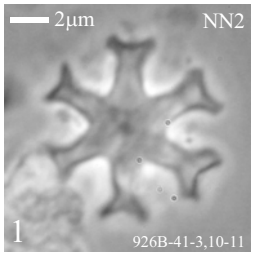
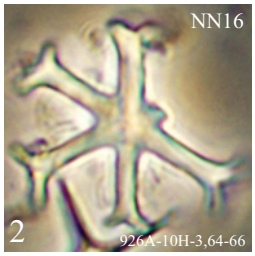

2µm
HOLOTYPE
NN9
1
926A-24-3,20.5-22.5
D. triuncinus
HOLOTYPE
NN9
2
NN9
3
KR23425
D. triuncinus
NN9
4
926A-24-3,20.5-22.5
D. bolivariae
NN9
5
926A-24-2,91-93
D. hamatus (<15)
HOLOTYPE
NN9
6
KR23425
D. bolivariae
NN9
7
926A-25-1,35-37
D. hamatus (<15)
NN9
8
KR23425
D. hamatus (<15)
NN9
9
KR23425
D. calcaris
NN9
10
KR23425
D. hamatus (>15)
502-50-1, 19-20
NN11a
11
D. neohamatus
NN9
12
D. calcaris
NN11a
13
926B-20-2,37-38
D. pachyloeblichii
NN11a
14
NN11a
15
502-48-1, 90-91
D. pachyloeblichii
HOLOTYPE
NN11a
16
502-48-1, 90-91
D. pachyloeblichii
NN11b
17
926A-20H-3, 50-51
D. loeblichii
HOLOTYPE
NN11a
18
502-50-1, 19-20
D. breviloeblichii
NN11a
19
926B-20-6,133-134
D. breviloeblichii
NN11a
20
GoM
D. breviloeblichii
NN11a
21

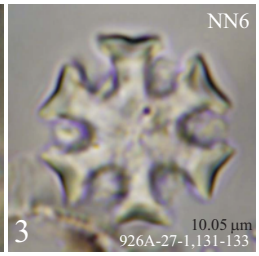
Plate 5



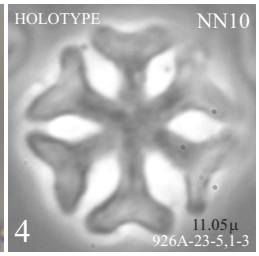
D. variabilis



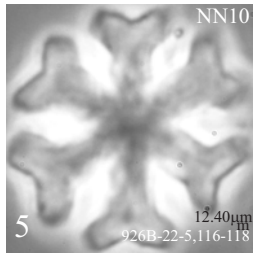
D. variabilis



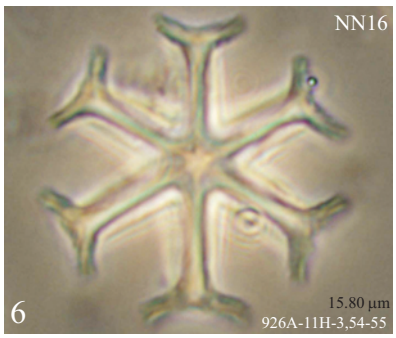
D. pansulus



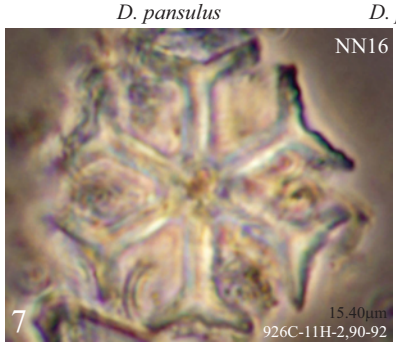
D. pansulus



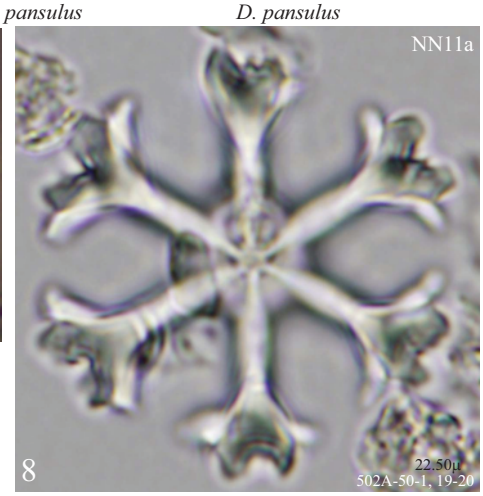
D. pansulus



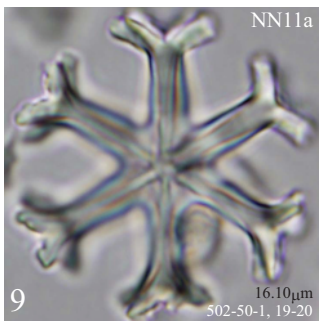
D. pansus



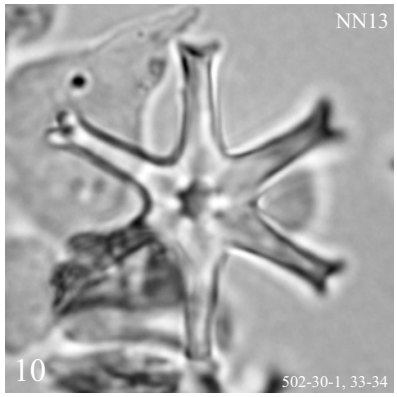
D. pansus



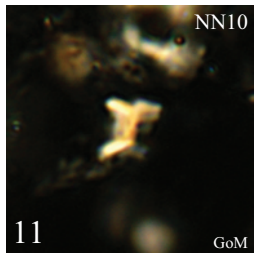
D. icarus



D. icarus



D. decorus



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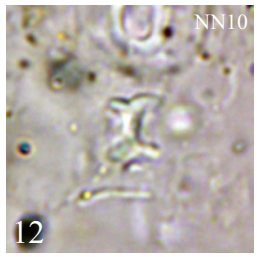

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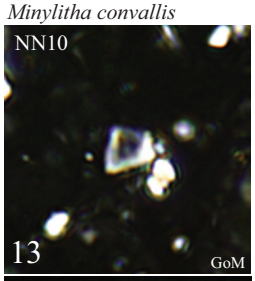

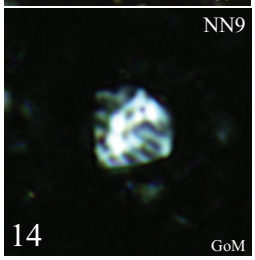

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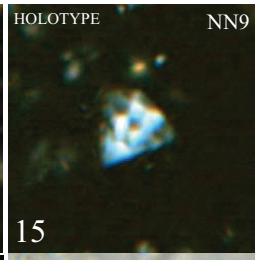

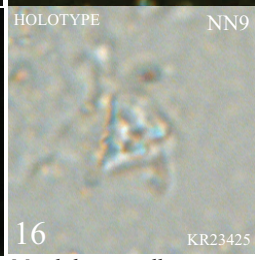

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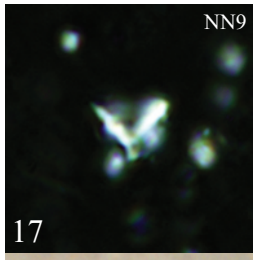

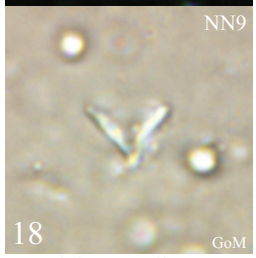

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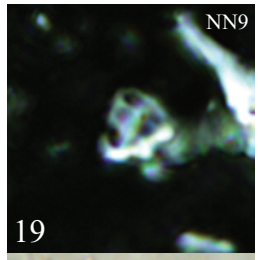

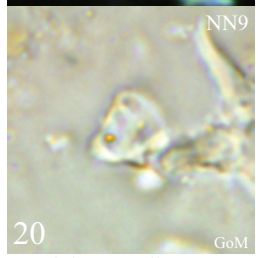

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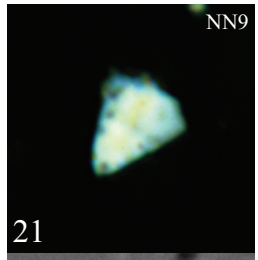

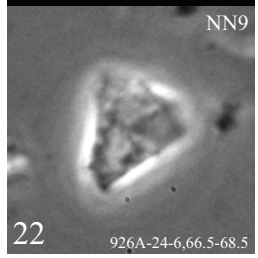

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