Prell, W. L., Niitsuma, N., et al., 1991
Proceedings of the Ocean Drilling Program, Scientific Results, Vol. 117

2. COCCOLITH BIOSTRATIGRAPHY OF THE ARABIAN SEA[1]

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ABSTRACT

A total of 21 calcareous nannofossil datums was found in the upper Pliocene and Quaternary sediments recovered from the ocean floor of the North Atlantic during DSDP Leg 94. These datums were correlated to magnetostratigraphy, and ages were estimated by interpolation between magnetic reversals.

Calcareous nannofossil assemblages from 549 samples recovered during ODP Leg 117 were studied in order to estimate the age of the sediments of Sites 720, 721, 722, and 731 drilled at the Indus Fan and the Owen Ridge in the Arabian Sea, Indian Ocean. We also showed that the datums above mentioned can be traced into the Indian Ocean. Two new species, namely *Helicosphaera omanica* and *Reticulofenestra ampla*, are described.

INTRODUCTION

Takayama and Sato (1987) investigated calcareous nannofossil floras from Cenozoic sediments of the North Atlantic Ocean. They recognized a total of 12 calcareous nannofossil datums in the Quaternary sediments. Correlation of these datums to magnetostratigraphy provided age estimates through interpolation between magnetic reversals. Subsequently, Sato (1989) restudied the calcareous nannofossil assemblages at Hole 610A and recognized one additional datum in the Quaternary sequence. Very recently eight datums were described and dated in the upper Pliocene sediments at Site 607 by Kameo (1989).

In this report we describe the calcareous nannofossil assemblages and their stratigraphic changes at the Indus Fan and the Owen Ridge sites of ODP Leg 117 and discuss the basis for biostratigraphic age assignments. The main purpose of this investigation, however, is to show that the datums we recognized in the North Atlantic can be traced into the Indian Ocean.

METHODS

The outermost portion of each sample was removed to avoid floral contamination. Each sample was processed according to the following method outlined by Stradner and Papp (1961). Approximately 5 mg of the samples was stirred into about 20 mL of water in a small beaker. This beaker was placed in an ultrasonic cleaner at a moderate vibration setting for 5 s. After the heavier particles had settled, about 1 cm^3 was withdrawn with a straw from the upper layer of the suspension and placed on a square microscopic cover glass (18 × 18 mm). The liquid was allowed to dry on an electric hot plate set at approximately 40°C to 50°C. A drop of "Eukitt" was spread over the center of a micro slide glass (76 × 26 mm) and then the cover glass was pressed upside down onto it.

After the mounting reagent hardened completely, the micro slide was observed under the binocular polarizing microscope with an oil-immersion objective at a magnification of 1,500×. Except for a few samples, more than one thousand calcareous nannofossil specimens were identified. In addition, 200 specimens were counted at random in order to determine their relative frequencies of occurrence and their stratigraphic changes.

Range charts have been prepared for all samples examined. These charts show the numbers of specimens of calcareous nannofossils counted at random in each sample during the 200-specimen count; + indicates the presence of a species in a sample. The overall preservation of nannofossil floras was registered using one of three alphabetic designations (Steinmetz, 1979); G = good preservation—fossils lack evidence of dissolution or overgrowth; M = moderately good preservation—the majority of the specimens is slightly etched (fine structures are missing, but no diagnostic changes of form are evident in light microscopy; all taxa may be easily identified); and P = poor preservation—the majority of the specimens is deeply etched (identity of many centerless and fragmental specimens is questionable).

DATUMS AND ZONES

Datums

A total of 22 holes was drilled at six sites during DSDP Leg 94, on a roughly south-southwest to north-northeast transect in the North Atlantic Ocean from 37°N to 53°N. As mentioned above, Takayama and Sato (1987) studied coccolith assemblages in the Cenozoic sediments at these sites and recognized 12 datums in the Quaternary sequences. Subsequently, Sato (1989) found another datum. The results of his study from Hole 610A are shown in Figure 1. The first appearance of *Reticulofenestra* sp. A is also a reliable datum in the Pleistocene sequence. Sato estimated the absolute age of this datum through direct correlation to magnetostratigraphy.

A total of 13 coccolith biohorizons is useful for the Quaternary sequences. As a matter of convenience, we will give numbers to these datums in descending order from 1 to 13. These datums are as follows (LAD and FAD mean last and first appearance datums):

Datum 1. LAD *Helicosphaera inversa*
Datum 2. FAD *Emiliania huxleyi*
Datum 3. LAD *Pseudoemiliania lacunosa*
Datum 4. FAD *Helicosphaera inversa*
Datum 5. Top of acme of *Reticulofenestra* sp. A (= LAD *Reticulofenestra asanoi*)
Datum 6. FAD *Gephyrocapsa parallela*
Datum 7. FAD *Reticulofenestra* sp. A (= Bottom of acme of *Reticulofenestra asanoi*)
Datum 8. LAD *Gephyrocapsa* (large: larger than 6 μm)
Datum 9. LAD *Helicosphaera sellii*
Datum 10. FAD *Gephyrocapsa* (large: larger than 6 μm)
Datum 11. LAD *Calcidiscus macintyrei* and FAD *Gephyrocapsa oceanica*

[1] Prell, W. L., Niitsuma, N., et al., 1991. *Proc. ODP, Sci. Results*, 117: College Station, TX (Ocean Drilling Program).
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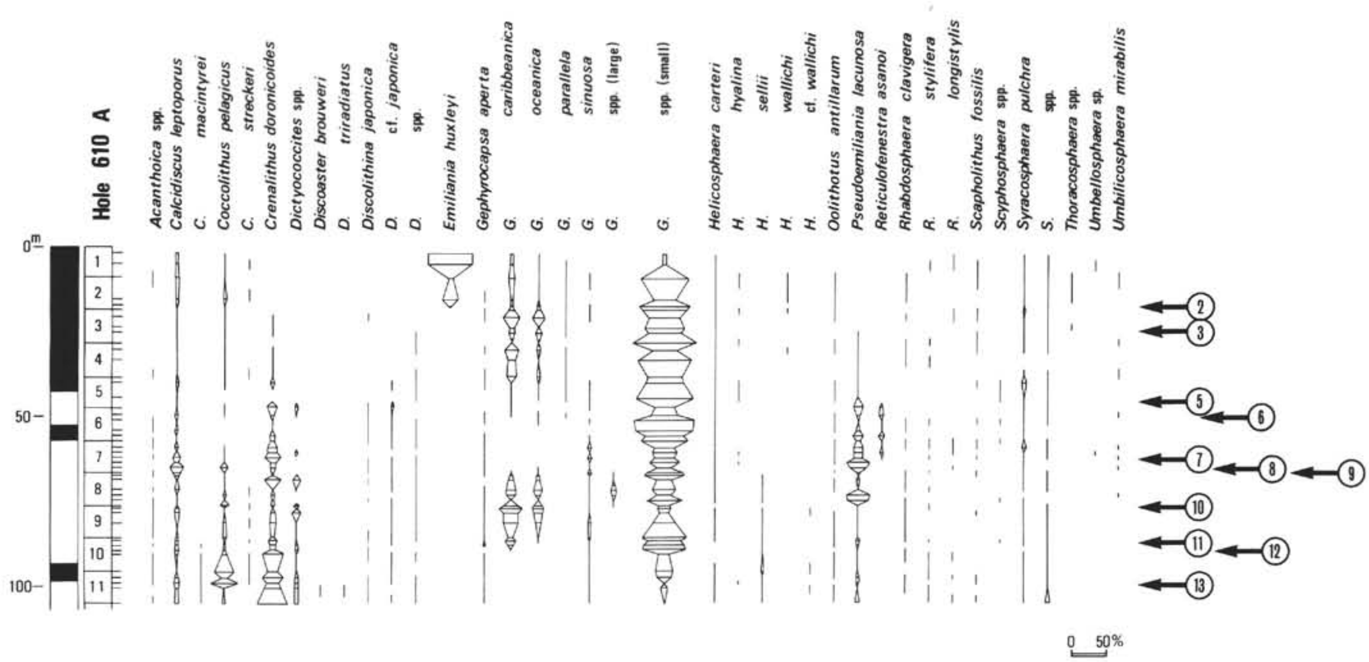

Figure 1. Stratigraphic distribution and relative abundance of calcareous nannofossil species in Hole 610A of DSDP Leg 94.

Datum 12. FAD *Gephyrocapsa caribbeanica*
Datum 13. LAD *Discoaster brouweri*

Quaternary magneto- and biostratigraphic relationships for each site of DSDP Leg 94 are shown in Figure 2. As is evident from Figure 2, *Helicosphaera inversa* is found only at Sites 606, 607, and 608, and, therefore, the LAD and FAD of this species (Datum 1 and Datum 4) cannot be recognized at high latitudes. The FAD of *Gephyrocapsa caribbeanica* (Datum 12) is located just above the Olduvai Event at Sites 606, 607, 609, and 610. At Site 611, however, this datum is slightly older and is within the Olduvai Event. The synchroneity of all other datums is demonstrated.

Based on the sequential changes of the floras at Site 607, Kameo (1989) recognized eight datums in the upper Pliocene (Fig. 3). The ages of these datums were estimated based on correlation to magnetostratigraphy. For convenience we will give numbers to these datums from 14 to 21 in descending order, as follows:

Datum 14. Bottom of acme of *Gephyrocapsa*
Datum 15. Top of "upper acme" of *Crenalithus doronicoides*
Datum 16. LAD *Discoaster pentaradiatus*
Datum 17. LAD *Discoaster surculus*
Datum 18. LAD *Discoaster tamalis*
Datum 19. LAD *Reticulofenestra ampla*, n. sp.
Datum 20. Top of "lower acme" of *Crenalithus doronicoides*
Datum 21. LAD *Reticulofenestra pseudoumbilica*

As a result, a total of 21 nannofossil datums can be recognized in the Quaternary and upper Pliocene sequences from the North Atlantic Ocean.

Figure 4 shows Quaternary and late Pliocene calcareous nannofossil datums, and the relationship between these datums and magnetostratigraphy. Quaternary and late Pliocene calcareous nannofossil biostratigraphy are discussed based on these datums in the following sections.

Zones

Various Cenozoic calcareous nannofossil zonation schemes based primarily on land or epicontinental sections have been established by numerous investigators. Among them, the "Standard Calcareous Nannofossil Zonation" established by Martini (1971) is widely used. These land-based zonation schemes, however, are not always useful when dealing with deep-sea sediments. Because of this, a comprehensive zonal scheme was proposed by Bukry (1971, 1973, 1975) for low-latitude deep-sea sections. Subsequently, Okada and Bukry (1980) introduced code numbers to this zonation. The zonal scheme established by Martini (1971) is employed throughout this report mainly to make zonal and geological age assignments of the sequences older than early Pliocene.

SUMMARY OF NANNOFOSSIL BIOSTRATIGRAPHY OF THE INDUS FAN AND THE OWEN RIDGE

During Leg 117, a total of 25 holes was drilled at 12 sites in the Arabian Sea, Indian Ocean. Among them, one hole was drilled in the Indus Fan (Site 720) and eight holes at three sites on the Owen Ridge (Sites 721, 722, and 731) (Table 1 and Fig. 5). Cenozoic sediments were recovered primarily by continuous hydraulic piston coring (HPC) and use of the extended core barrel (XCB). Abundant coccoliths and discoasters were found throughout nearly all of the cores. Each site is considered separately, and an overview of the biostratigraphic results are shown in Table 2. Tables 3–6 (range charts) are on microfiche (in back pocket).

Indus Fan

Site 720 (Table 3, Fig. 6)

Site 720 is located on the westernmost part of the middle Indus Fan, about 360 km south-southwest of previous DSDP Site 222. Sediments recovered at this site are Pleistocene in age, and

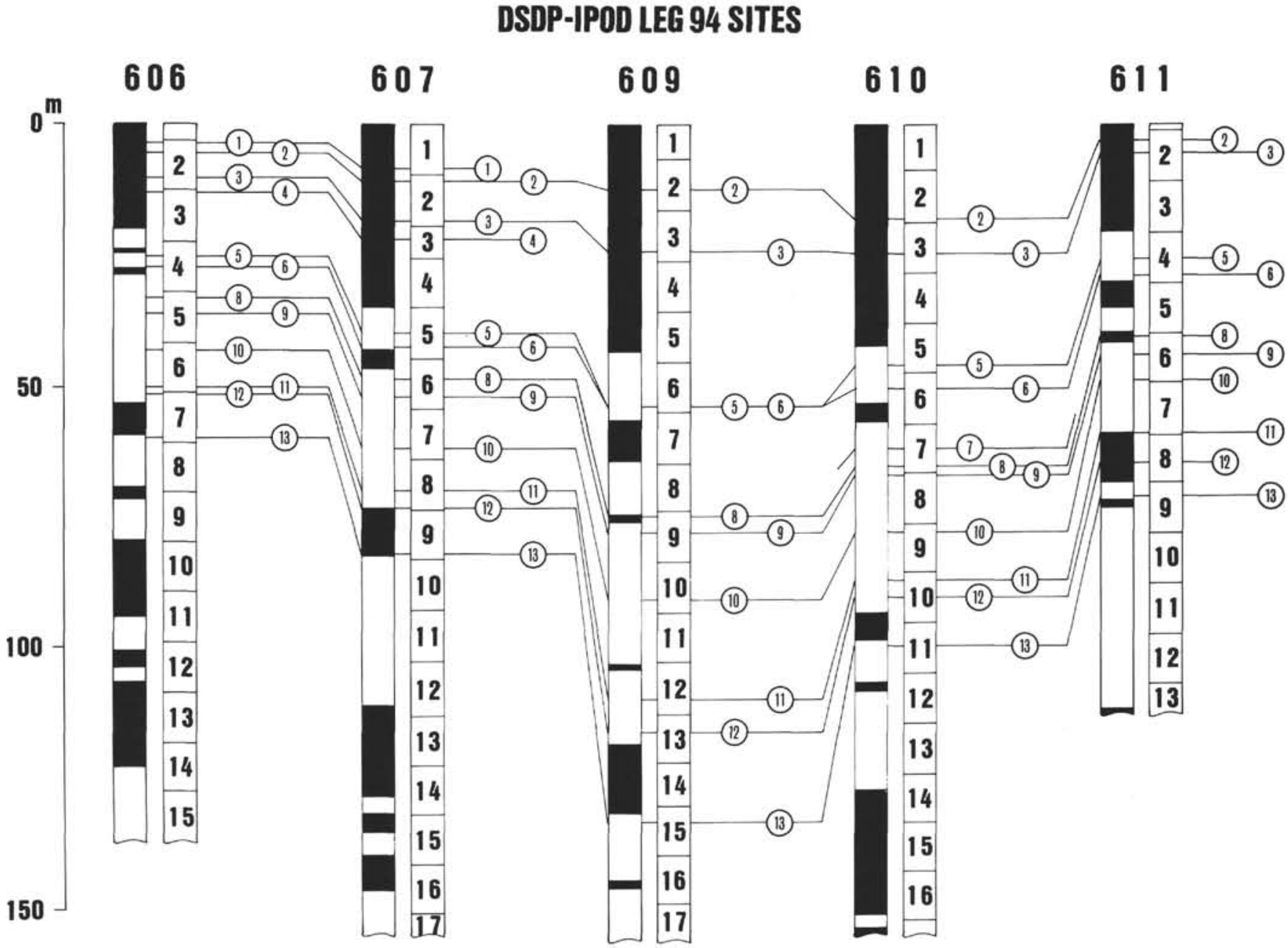

Figure 2. Quaternary magneto- and biostratigraphic relationships at each site of DSDP Leg 94.

consist of turbiditic clastic sediments intercalated with pelagic nannofossil ooze.

Calcareous nannofossils occur throughout the single hole cored, where they range from abundant to rare. Pelagic oozes contain well to moderately preserved, diverse assemblages of nannofossils. Unfortunately, most of the material recovered consisted of turbiditic sequences, in which the nannofossils were moderately to poorly preserved and present in low concentrations. Due to these circumstances, the age assignment for the bottom of the hole is not reliable.

Hole 720A

Helicosphaera inversa is very rare, and therefore Datums 1 and 4 (LAD and FAD *Helicosphaera inversa*) are uncertain. Fairly abundant *Emiliania huxleyi* are present in the first two samples, Sample 117-720A-1H-1, 100–101 cm, and 117-720A-1H-3, 100–101 cm. Although a few specimens which probably can be referred to the same species are found in several samples below (for example in Sample 117-720A-3H-1, 99–100 cm), Datum 2 (FAD *Emiliania huxleyi*) is placed tentatively between Samples 117-720A-1H-3, 100–101 cm, and 117-720A-1H-5, 100–101 cm. The last occurrence of *Pseudoemiliania lacunosa* (Datum 3) is in Core 117-720A-5X, between Samples 117-720A-4X-CC and 117-720A-5X-3, 144–145 cm. A few specimens of this species in Samples 117-720A-1H-3, 100–101 cm, and 117-720A-2H-3, 100–101 cm, are regarded as reworked. Therefore, Sample 117-720A-1H-5, 100–101 cm, through Sample 117-720A-4X-CC contain neither *E. huxleyi* nor *P. lacunosa*. Small specimens of *Gephyrocapsa* which are slightly smaller than 4 μm in diameter are very abundant in Samples 117-720A-2H-1, 100-101 cm, 117-720A-4X-CC, and 117-720A-5X-3, 144–145 cm. The state of preservation of calcareous nannofossils in Samples 117-720A-7X-2, 75–76 cm, and 117-720A-7X-CC is very poor. Fairly abundant *Pseudoemiliania lacunosa* and *Umbilicosphaera mirabilis* are found in Samples 117-720A-11X-3, 80–81 cm. Samples 117-720A-14X-CC down to 117-720A-27X-CC are characterized by the sporadic occurrences of typical *Reticulofenestra asanoi*. The occurrence of this species in Samples 117-720A-14X-CC, 117-720A-16X-1, 100–101 cm, and 117-720A-17X-CC may be considered to be reworked. Therefore Datum 5 (LAD *Reticulofenestra asanoi*) is placed between Samples 117-720A-17X-CC and 117-720A-19X-2, 33–34 cm. Datum 7 (bottom of acme of *Reticulofenestra asanoi*) is placed between Samples 117-720A-27X-CC and 117-720A-28X-CC. *Gephyrocapsa parallela* is found only in and above Sample 117-720A-19X-CC. Therefore, Datum 6 (FAD *Gephyrocapsa parallela*) is present between Samples 117-720A-19X-CC and 117-720A-20X-2, 70–71 cm. It is noteworthy that *Helicosphaera omanica*, n. sp. is fairly abundant below this datum. As comparatively large *Gephyrocapsa* (larger than 6 μm in diameter; see Takayama and Sato, 1987, p. 691) are concentrated in Samples 117-720A-30X-1, 100–101 cm, and 117-720A-30X-3, 100–101 cm, Datums 8 and 10 (LAD and FAD large *Ge-*

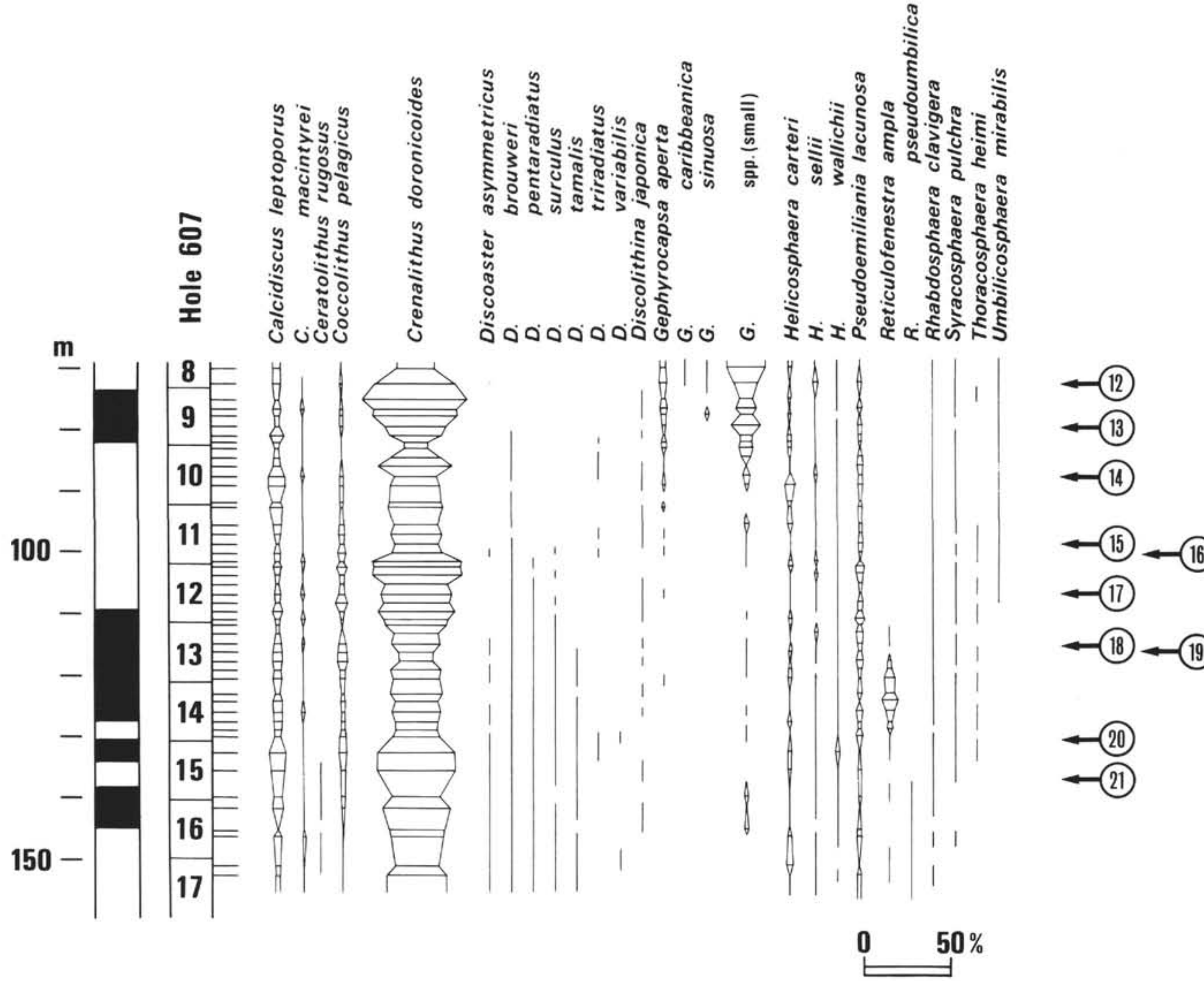

Figure 3. Stratigraphic distribution and relative abundance of calcareous nannofossil species in Hole 607 of DSDP Leg 94.

phyrocapsa) are placed between Samples 117-720A-29X-CC and 117-720A-30X-1, 100–101 cm, and Samples 117-720A-30X-3, 100–101 cm, and 117-720A-30X-5, 100–101 cm, respectively. *Helicosphaera sellii* is found as high as Sample 117-720A-30X-1, 100–101 cm. Judging from the state of preservation and the abundance, however, specimens in Samples 117-720A-30X-1, 100–101 cm, and 117-720A-30X-3, 100–101 cm, are considered to be reworked. Therefore, Datum 9 (LAD *Helicosphaera sellii*) is in Core 117-720A-30X, between Samples 117-720A-30X-3, 100–101 cm, and 117-720A-30X-5, 100–101 cm. Therefore, Datums 9 and 10 are in the same interval. This may suggest that the sediments which contain Datums 9 and 10 are very thin or missing. A few specimens of *Calcidiscus macintyrei* are recorded in Samples 117-720A-30X-1, 100–101 cm, 117-720A-30X-5, 100–101 cm, and 117-720A-32X-2, 53–54 cm. However, common occurrences of typical specimens of this species are recognized as high as Sample 117-720A-39X-1, 4–5 cm. *Gephyrocapsa oceanica*, which are larger than 4 μm in diameter (see Takayama and Sato, 1987, p. 691) do not occur below Sample 117-720A-37X-1, 14–15 cm. Samples 117-720A-37X-CC and 117-720A-38X-CC are almost barren. Therefore, Datum 11 (FAD *Gephyrocapsa oceanica* and LAD *Calcidiscus macintyrei*) is placed between Samples 117-720A-37X-1, 14–15 cm, and 117-720A-39X-1, 4–5 cm. Below this datum, *Gephyrocapsa caribbeanica* which is larger than 4 μm in diameter (see Takayama and Sato, 1987, p. 691) occurs only in Sample 117-720A-42X-CC. Therefore, Datum 12 (FAD *Gephyrocapsa caribbeanica*) may be slightly below this sample. The deepest sample (Sample 117-720A-43X-CC) contains a single specimen of *Discoaster pentaradiatus*. Judging from the state of preservation of this asterolith, it is considered to be reworked. Therefore, the bottom of this core may be above Datum 13 (LAD *Discoaster brouweri*). However, as mentioned above, the nannofossils are poorly preserved and present in low concentration in the lowest part of this hole. Therefore, age assignment for the bottom of this core has low confidence.

A trace of Cretaceous and Tertiary reworked specimens such as *Chiastozygus litterarius*, *Cretarhabdus* sp., *Eiffelithus turriseiffelii*, *Micula decussata*, *Prediscosphaera* sp., *Tranolithus phacelosus*, *Watznaueria barnesae*, *Dictyococcites bisecta*, *Discoaster barbadiensis*, *D. saipanensis*, *Ericsonia formosa*, *Cyclicargolithus floridanus*, and *Sphenolithus heteromorphus* occur throughout the recovered section. As is evident in Figure 6, these reworked specimens are fairly abundant in the lower half of the section. Cretaceous specimens are especially dominant in

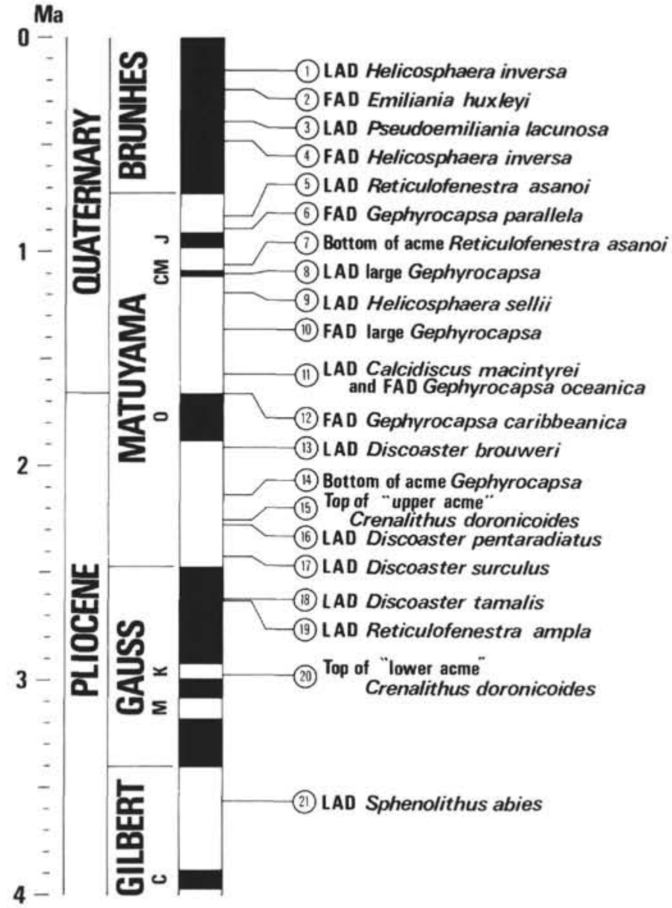

Figure 4. Calcareous nannofossil datums and the relation to magnetostratigraphy (J, Jaramillo Event; CM, Cobb Mountain Event; O, Olduvai Event; K, Kaena Event; M, Mammoth Event; C, Cochiti Event).

Table 1. Locations of studied sites of ODP Leg 117.

Hole	Latitude	Longitude	Water depth (m)
720A	16°07.796′N	60°44.621′E	4037.5
721A	16°40.636′N	59°51.879′E	1944.8
721B	16°40.636′N	59°51.879′E	1944.8
721C	16°40.636′N	59°51.879′E	1944.8
722A	16°37.312′N	59°47.755′E	2027.8
722B	16°37.312′N	59°47.755′E	2027.8
731A	16°28.229′N	59°42.149′E	2365.8
731B	16°28.229′N	59°42.149′E	2365.8
731C	16°28.229′N	59°42.149′E	2365.8

Samples 117-720A-23X-CC, 117-720A-28X-CC, and 117-720A-41X-CC, where these specimens comprise more than 20% of the flora. It is also noteworthy that occurrences of *Braarudosphaera bigelowi*, which is considered by Martini (1967) and Takayama (1972) to be a typical shallow-water species, are recognized in Samples 117-720A-3H-CC, 117-720A-32X-2, 53–54 cm, and 117-720A-41X-CC.

Owen Ridge

Site 721 (Table 4, Fig. 7)

Three holes were drilled at near the crest of the Owen Ridge in the western Arabian Sea to recover a continuous upper Neogene section of pelagic sediments that record changes in the monsoonal circulation system. The site is, therefore, situated above the regional carbonate lysocline to avoid major dissolution changes in the calcareous deposits. The section recovered from this site ranges in age from late Holocene to early Miocene. Calcareous nannofossils are abundant throughout the cores with the exception of the lowest part of Hole 721B. The flora is characterized by the absence of some tropical species since the late Miocene.

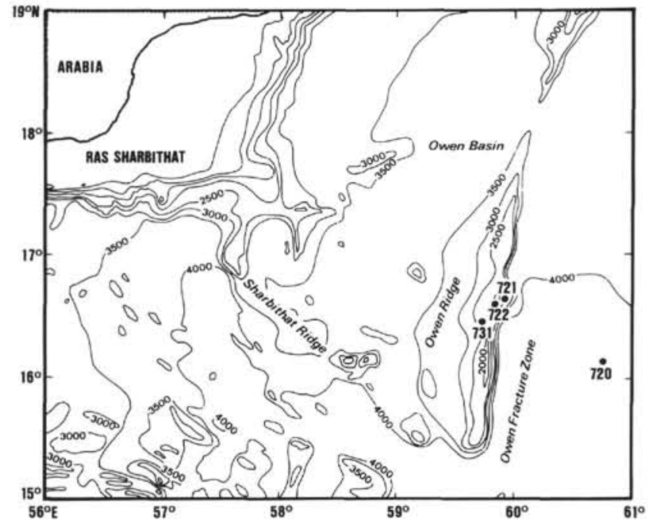

Figure 5. Location map of Sites 720, 721, 722, and 731, ODP Leg 117.

Hole 721A

In this hole, *Helicosphaera inversa* occurs sporadically, and the stratigraphic positions of Datums 1 and 4 (LAD and FAD *Helicosphaera inversa*) are, therefore, uncertain. Samples 117-721A-1H-1, 115–117 cm, down to 117-721A-1H-6, 115–117 cm, contain abundant typical *Emiliania huxleyi*. Though a trace of specimens similar to *E. huxleyi* also occurs below these samples, Datum 2 (FAD *Emiliania huxleyi*) is placed between Samples 117-721A-1H-6, 115–117 cm, and 117-721A-1H-CC. In Sample 117-721A-1H-3, 115–117 cm, *Scapholithus fossilis* is comparatively abundant. Samples 117-721A-1H-CC through 117-721A-2H-5, 115–117 cm, contain abundant tiny specimens of *Gephyrocapsa*; Samples 117-721A-2H-3, 115–117 cm, and 117-721A-2H-4, 115–117 cm, contain many gephyrocapsid specimens which are 2–3 μm in diameter. The presence of *Pseudoemiliania lacunosa* is recognized for the first time in Sample 117-721A-2H-5, 115–117 cm. Therefore, Datum 3 (LAD *Pseudoemiliania lacunosa*) is placed somewhere between Samples 117-721A-2H-4, 115–117 cm, and 117-721A-2H-5, 115–117 cm. Samples 117-721A-3H-CC through 117-721A-4H-2, 115–117 cm, contain *Gephyrocapsa parallela* together with *Reticulofenestra asanoi*. Therefore, these three samples belong to the interval between Datum 5 (LAD *Reticulofenestra asanoi*) and Datum 6 (FAD *Gephyrocapsa parallela*). *Reticulofenestra asanoi* is found down to Sample 117-721A-4H-5, 134–136 cm. Therefore, Datum 7 (bottom of acme of *Reticulofenestra asanoi*) is placed between Samples 117-721A-4H-5, 134–136 cm, and 117-721A-4H-6, 3–5 cm. The interval represented by Samples 117-721A-4H-3, 115–117 cm, down to 117-721A-4H-CC is characterized by the abundant occurrences of small *Gephyrocapsa* of about 2–3 μm in diameter. *Gephyrocapsa* larger than 4 μm such as *Gephyrocapsa caribbeanica* and *G. oceanica* are very rare or absent in this interval. It is also worthy of note that the abundant occurrences of a peculiar *Helicosphaera* species, *Helicosphaera omanica*, n. sp., are recognized as high as Sample 117-721A-4H-3, 115–117 cm. *Ge-*

Table 2. Calcareous nannofossil datum and zone age assignment of studied samples in the present investigation. Concerning the Pliocene/Pleistocene boundary, refer to Sato et al. (1988).

AGE		DATUMS	ZONES	SITE 720	SITE 721	SITE 722	SITE 731
QUATERNARY			NN 21 Emiliania huxleyi Zone	117-720A-1H-1,100-101 117-720A-1H-3,100-101	117-721A-1H-1,115-117 117-721A-1H-6,115-117	117-722A-1H-1,115-117 117-722A-1H,CC	117-731A-1H-1,115-117 117-731A-1H,CC
		DATUM 2					
			NN 20 Gephyrocapsa oceanica Zone	117-720A-1H-5,100-101 117-720A-4X,CC	117-721A-1H,CC 117-721A-2H-4,115-117	117-722A-2H-1,115-117 117-722A-2H-5,115-117	117-731A-2H-1,115-117 117-731A-2H-6,115-117
		DATUM 3					
				117-720A-5X-3,144-145 117-720A-17X,CC	117-721A-2H-5,115-117 117-721A-3H-6,112-114	117-722A-2H-6,115-117 117-722A-4H-2,118-119	117-731A-2H,CC 117-731A-5H-2,115-117
		DATUM 5					
				117-720A-19X-2,33-34 117-720A-19X,CC	117-721A-3H,CC 117-721A-4H-2,115-117	117-722A-4H-3,115-117 117-722A-4H-5,115-117	117-731A-5H-3,115-117 117-731A-5H-4,115-117
		DATUM 6					
				117-720A-20X-2,70-71 117-720A-27X,CC	117-721A-4H-3,115-117 117-721A-4H-5,134-136	117-722A-4H-6,115-117 117-722A-5H-1,115-117	117-731A-5H-5,115-117 117-731A-5H,CC
		DATUM 7					
				117-720A-28X,CC 117-720A-29X,CC	117-721A-4H-6,3-5 117-721A-4H,CC	117-722A-5H-2,115-117 117-722A-5H-3,115-117	117-731A-6H-1,115-117 117-731A-6H-3,115-117
		DATUM 8					
			NN 19 Pseudoemiliania lacunosa Zone	117-720A-30X-1,100-101 117-720A-30X-3,100-101	117-721A-5H-1,115-117 117-721A-5H,CC	117-722A-5H-4,115-117 117-722A-6H-2,115-117	117-731A-6H-4,115-117 117-731A-7H-2,115-117
		DATUM 9					
		DATUM 10					
				117-720A-30X-5,100-101 117-720A-37X-1,14-15		117-722A-6H-3,115-117	117-731A-7H-3,115-117 117-731A-7H-6,115-117
		DATUM 11					
				117-720A-39X-1,4-5 117-720A-42X,CC	117-721A-6H-1,115-117 117-721A-6H-2,115-117	117-722A-6H-4,115-117	117-731A-7H,CC
		DATUM 12					
PLIOCENE	LATE				117-721A-6H-3,115-117 117-721A-7H-2,115-117	117-722A-6H-5,115-117 117-722A-7H-4,114-116	117-731A-8X-1,115-117 117-731A-9X-5,115-117
		DATUM 13					
					117-721A-7H-3,115-117 117-721A-7H-6,115-117	117-722A-7H-5,115-117 117-722A-8H-1,115-117	117-731A-9X,CC 117-731A-10X-2,115-117
		DATUM 14					
			NN 18 Discoaster brouweri Zone		117-721A-7H,CC	117-722A-8H-2,115-117	117-731A-10X-3,115-117
		DATUM 15					
					117-721A-8H-1,115-117 117-721A-8H-2,115-117	117-722A-8H-3,115-117 117-722A-8H-4,114-116	117-731A-10X-4,115-117 117-731A-10X-6,115-117
		DATUM 16					
			NN 17 Discoaster pentaradiatus Zone		117-721A-8H-3,115-117 117-721A-8H-5,115-117	117-722A-8H-5,115-117	117-731A-10X,CC 117-731A-11X-1,115-117
		DATUM 17					
					117-721B-9H-2,115-117		
		DATUM 18					
			NN 16 Discoaster surculus Zone		117-721B-9H-5,115-117	117-722A-9H-3,103-105	
		DATUM 19					
					117-721B-9H-6,115-117 117-721B-10X,CC	117-722A-9H-4,115-117 117-722A-10X-5,123-125	
		DATUM 20					
					117-721B-11X-1,115-117 117-721B-12X,CC	117-722A-10X,CC 117-722A-11X,CC	
		DATUM 21					
	EARLY		NN 15 Reticulofenestra pseudoumbilica Zone		117-721B-13X-1,115-117	117-722A-12X-1,116-118	117-731A-11X-2,116-118
			NN 14 Discoaster asymmetricus Zone				
			NN 13 Ceratolithus rugosus Zone				
			NN 12 Amaurolithus tricorniculatus Zone		117-721B-19X-4,115-117	117-722A-17X,CC	117-731A-12X-5,115-117
MIOCENE	LATE		NN 11 Discoaster quinqueramus Zone		117-721B-19X-5,115-117 117-721B-28X-1,105-107	117-722A-18X-1,115-117 117-722B-29X,CC	117-731A-12X-6,115-117 117-731A-17X,CC
			NN 10 Discoaster calcaris Zone		117-721B-28X-2,107-109 117-721B-30X-2,81-83	117-722B-30X,CC 117-722B-32X,CC	117-731A-18X-1,135-137 117-731A-21X,CC
	MIDDLE		NN 9 Discoaster hamatus Zone		117-721B-30X,CC 117-721B-33X-1,115-116	117-722B-33X-1,115-116 117-722B-34X,CC	117-731A-22X-2,111-113 117-731A-25X,CC
			NN 8 Catinaster coalitus Zone		117-721B-33X-2,115-116	117-722B-35X,CC	117-731A-26X-3,117-119
			NN 7 Discoaster kugleri Zone			117-722B-40X-2,110-111	117-731A-29X,CC
			NN 6 Discoaster exilis Zone			117-722B-40X,CC	117-731A-30X-2,115-116 117-731A-31X-1,115-116
			NN 5 Sphenolithus heteromorphus Zone		117-721B-33X,CC	117-722B-41X-2,32-33	117-731A-31X,CC
	EARLY		NN 4 Helicosphaera ampliaperta Zone		117-721B-43X,CC	117-722B-46X-2,115-116	117-731A-43X-4,105-106
			NN 3 Spenolithus belemnos Zone			117-722B-58X-5,7-8	117-731A-43X,CC
			NN 2 Discoaster druggi Zone				117-731C-3W-2,78-79
			NN 1 Triquetrorhabdulus carinatus Zone				?
OLIGOCENE			NP 25 Sphenolithus ciperoensis Zone				117-731C-13W-5,73-74

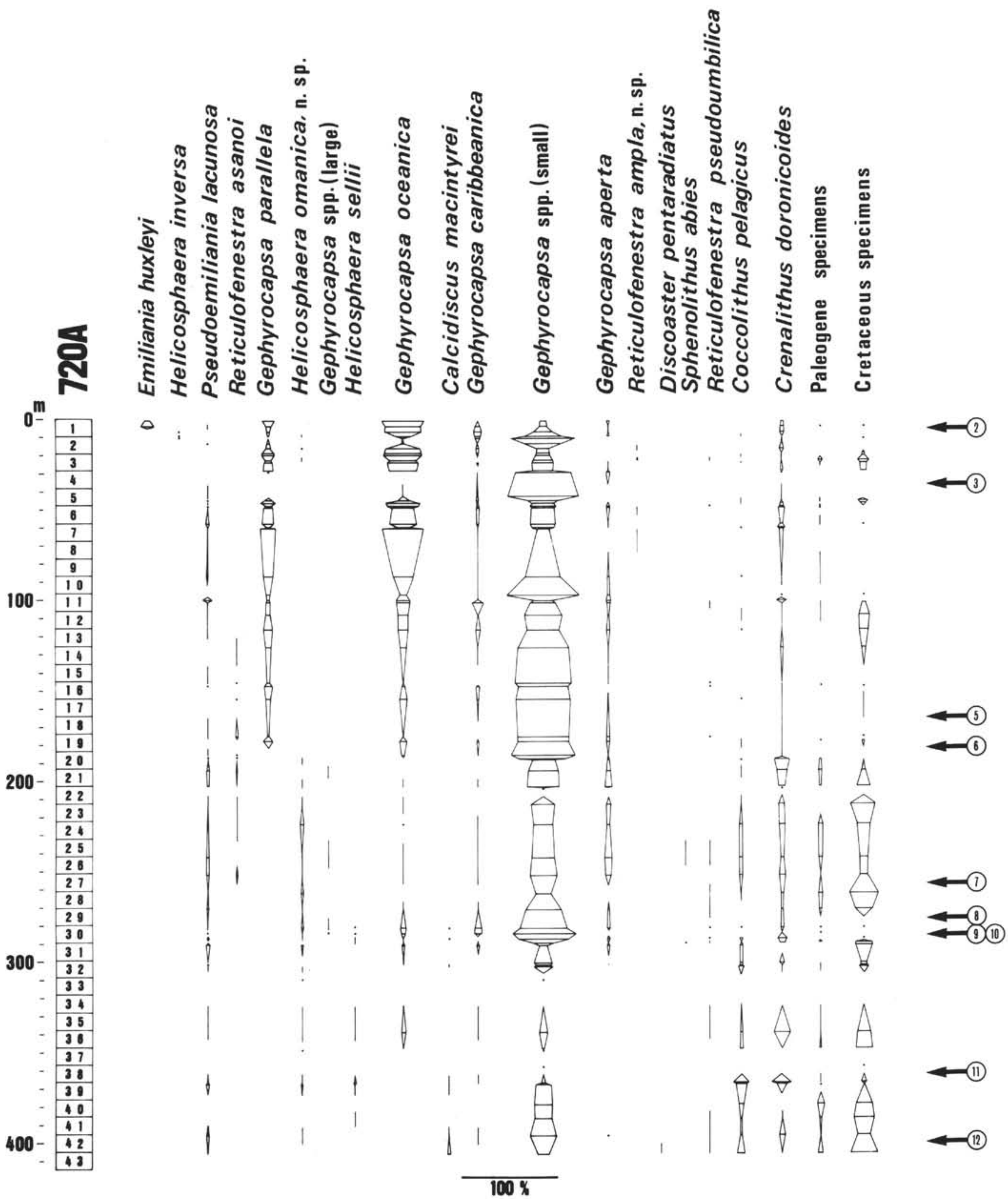

Figure 6. Stratigraphic distribution and relative abundance of selected calcareous nannofossil species in Hole 720A, ODP Leg 117.

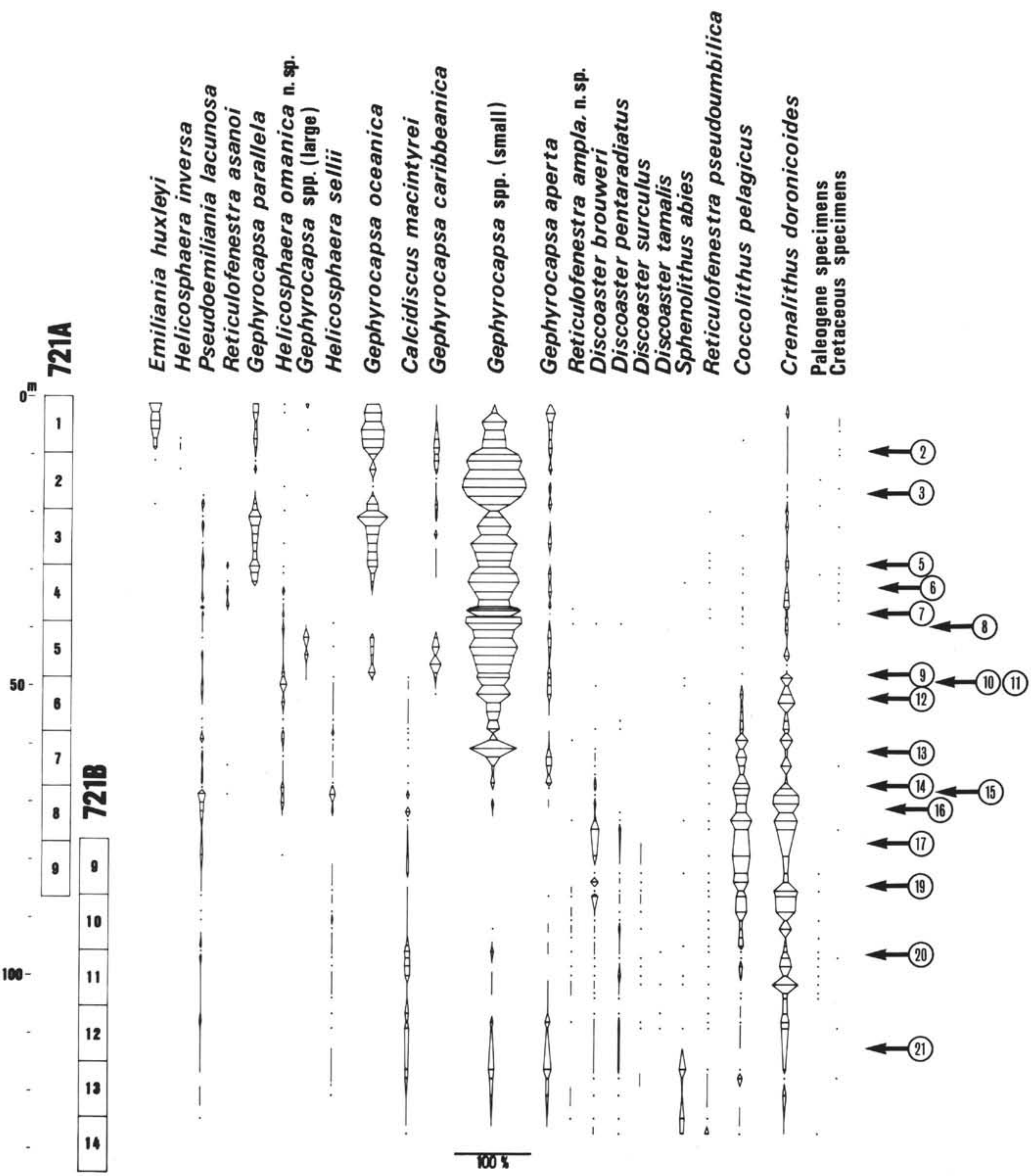

Figure 7. Stratigraphic distribution and relative abundance of selected calcareous nannofossil species in Holes 721A and 721B, ODP Leg 117.

phyrocapsa specimens larger than 6 μm are concentrated in the interval from Sample 117-721A-5H-1, 115–117 cm, through Sample 117-721A-5H-CC. However, they decrease in size rapidly in the lower half of this interval. Therefore, Datum 8 (LAD large *Gephyrocapsa*) is easily detected between Samples 117-721A-4H-CC and 117-721A-5H-1, 115–117 cm. Datum 10 (FAD large *Gephyrocapsa*) is slightly more difficult to recognize; it may be placed between Samples 117-721A-5H-CC and 117-721A-6H-1, 115–117 cm. *Helicosphaera sellii* is found as high as Sample 117-721A-5H-CC. However, judging from the state of preservation, the specimens in the uppermost sample are considered to be reworked. Consequently, Datum 9 (LAD *Helicosphaera sel-*

lii) is placed between Samples 117-721A-5H-CC and 117-721A-6H-1, 115–117 cm. *Gephyrocapsa oceanica* is found above Sample 117-721A-5H-CC and the occurrences of typical *Calcidiscus macintyrei* are recognized below Sample 117-721A-6H-1, 115–117 cm. Consequently Datum 9 (LAD *Helicosphaera sellii*), Datum 10 (FAD large *Gephyrocapsa*), and Datum 11 (LAD *Calcidiscus macintyrei* and FAD *Gephyrocapsa oceanica*) are placed between Samples 117-721A-5H-CC and 117-721A-6H-1, 115–117 cm. Judging from this, it is considered that a part of the lower Pleistocene sediments are missing. *Gephyrocapsa caribbeanica* occurs above Sample 117-721A-6H-2, 115–117 cm, and Datum 12 (FAD *Gephyrocapsa caribbeanica*) is detected between Sample 117-721A-6H-2, 115–117 cm and 117-721A-6H-3, 115–117 cm.

Calcareous nannofossil floras from Samples 117-721A-6H-3, 115–117 cm, through the bottom of this hole apparently indicate a late Pliocene age. These samples commonly contain *Calcidiscus leptoporus, C. macintyrei, Coccolithus pelagicus*, and *Pseudoemiliania lacunosa* together with some *Discoaster* species. The trace of *Discoaster brouweri* is recognized in Sample 117-721A-7H-2, 115–117 cm. Judging from the state of preservation of this asterolith, it is considered to be reworked. This species is certainly found below Sample 117-721A-7H-3, 115–117 cm, and therefore Datum 13 (LAD *Discoaster brouweri*) is placed between Samples 117-721A-7H-2, 115–117 cm, and 117-721A-7H-3, 115–117 cm. Sample 117-721A-7H-2, 115–117 cm, is also characterized by abundant occurrences of small specimens of *Gephyrocapsa* which form 62% of the total flora. These small *Gephyrocapsa* and *G. aperta* are dominant down to Sample 117-721A-7H-6, 115–117 cm, but below this sample only a few specimens are recognized. Therefore, Datum 14 (bottom of acme *Gephyrocapsa*) is placed between Samples 117-721A-7H-6, 115–117 cm, and 117-721A-7H-CC. *Crenalithus doronicoides*, which is larger than 4 μm in diameter, occurs almost throughout this hole. Samples 117-721A-8H-1, 115–117 cm, and 117-721A-8H-2, 115–117 cm, contain dominant specimens of *Crenalithus doronicoides*, many of which are larger than 5 μm. Consequently, Datum 15 (top of "upper acme" of *Crenalithus doronicoides*) is recognized in the interval slightly above Sample 117-721A-8H-1, 115–117 cm. Samples 117-721A-8H-1, 115–117 cm, and 117-721A-8H-2, 115–117 cm, are also characterized by the abundant occurrences of some *Helicosphaera* species. Datum 16 (LAD *Discoaster pentaradiatus*) is placed between Samples 117-721A-8H-2, 115–117 cm, and 117-721A-8H-3, 115–117 cm. *Discoaster surculus* occurs in and below Sample 117-721A-8H-6, 115–117 cm. Consequently, Datum 17 (LAD *Discoaster surculus*) is placed between Samples 117-721A-8H-5, 115–117 cm, and 117-721A-8H-6, 115–117 cm.

Hole 721B

Discoaster surculus occurs in and below Sample 117-721B-9H-2, 115–117 cm. Consequently, Datum 17 (LAD *Discoaster surculus*) is placed between Samples 117-721B-9H-1, 115–117 cm, and 117-721B-9H-2, 115–117 cm. *Helicosphaera omanica*, n. sp. is absent below Sample 117-721B-9H-4, 115–117 cm. Its first occurrence may be slightly below Datum 17. The sediments of Hole 117-721B contain limited numbers of *Discoaster tamalis*. Therefore, Datum 18 (LAD *Discoaster tamalis*) cannot be recognized. On the other hand, *Reticulofenestra ampla*, n. sp. is found in and below Sample 117-721B-9H-6, 115–117 cm. Therefore, Datum 19 (LAD *Reticulofenestra ampla*) is placed between Samples 117-721B-9H-5, 115–117 cm, and 117-721B-9H-6, 115–117 cm. Samples 117-721B-11X-1, 115–117 cm, through 117-721B-11X-4, 114–116 cm, contain a large number of specimens of *Crenalithus doronicoides*. They are larger than those of any other horizons in the upper Pliocene and often exceed 6 μm in diameter. Therefore, Datum 20 (top of "lower acme" of *Crenalithus doronicoides*) is recognized between Samples 117-721B-10X-CC and 117-721B-11X-1, 115–117 cm.

A drastic change in the nannofossil flora occurs between Samples 117-721B-12X-CC and 117-721B-13X-1, 115–117 cm. Below this horizon, *Reticulofenestra pseudoumbilica* and *Sphenolithus abies* are common. Therefore, Datum 21 (LAD *Reticulofenestra pseudoumbilica*) is placed between these two samples. The number of small *Gephyrocapsa* increases again in Sample 117-721B-12X-2, 115–117 cm, through Sample 117-721B-13X-4, 115–117 cm. Furthermore, the first occurrence of *Pseudoemiliania lacunosa* is recognized slightly below Datum 21.

Some species of ceratoliths and *Discoaster asymmetricus* are important zonal markers in the early Pliocene calcareous nannofossil zonation by Martini (1971). These species, however, are rare in this hole, and therefore, the zonal boundaries between NN15 and NN12 cannot be detected. *Discoaster berggreni* and *D. quinqueramus* are continuously present in Samples 117-721B-19X-5, 115–117 cm, through 117-721B-28X-1, 105–107 cm. Therefore, these samples belong to the upper Miocene Zone NN11. Sample 117-721B-28X-2, 107–109 cm, through Sample 117-721B-30X-2, 81–83 cm, are assigned to Zone NN10, based on the absence of *Discoaster quinqueramus* and *D. hamatus*.

Another change in species composition occurs at the boundary between NN11 and NN10, which is placed between Samples 117-721B-28X-1, 105–107 cm, and 117-721B-28X-2, 107–109 cm. Small placoliths such as *Crenalithus* cf. *doronicoides* and *Dictyococcites* cf. *productus* account for nearly 80% of the calcareous nannofossil flora above this boundary, whereas large-sized placoliths such as *Reticulofenestra pseudoumbilica* and *R. gelida* are abundant below. The occurrence of *Discoaster hamatus* suggests that Samples 117-721B-30X-CC through 117-721B-33X-1, 115–116 cm, can be correlated with Zone NN9. The upper and lower parts of this zone contain *Discoaster neohamatus* and *Catinaster coalitus*, respectively. Because of the absence of *Discoaster hamatus*, Sample 117-721B-33X-2, 115–116 cm, is assigned to Zone NN8.

The sediments below Sample 117-721B-33X-CC are characterized by abundant occurrences of *Cyclicargolithus floridanus*. *Sphenolithus heteromorphus* also occurs continuously from Samples 117-721B-33X-CC to 117-721B-43X-CC. As *Helicosphaera ampliaperta* is not found in this hole (it is known to be rare or absent in some regions of the South Atlantic and the Pacific; Perch-Nielsen, 1985), the occurrences of *Sphenolithus heteromorphus* suggest that these samples belong to Miocene Zone NN5 and Zone NN4. Therefore Zone NN7 and Zone NN6 are missing; a middle Miocene hiatus is inferred at this site. In the interval below Sample 117-721B-40X-2, 115–116 cm, calcareous nannofossils are rare and at the bottom of this hole (Sample 117-721B-44X-CC) they are barren.

Hole 721C

Nannofossil assemblages in Hole 721C are similar to those observed in Hole 721A and 721B.

Site 722 (Table 5, Fig. 8)

This site is located near the crest of the Owen Ridge in the Western Arabian Sea. Two holes were drilled at this site to recover a continuous upper Neogene sequence of pelagic sediments from an area of monsoonal upwelling.

Hole 722A

As is similar to the previous sites, *Helicosphaera inversa* occurs sporadically in this hole, and therefore Datums 1 and 4 (LAD and FAD *Helicosphaera inversa*) cannot be clearly detected. Samples 117-722A-1H-1, 115–117 cm, through 117-722A-1H-CC are characterized by the common occurrences of *Emiliania huxleyi*. Therefore, Datum 2 (FAD *Emiliania huxleyi*) is

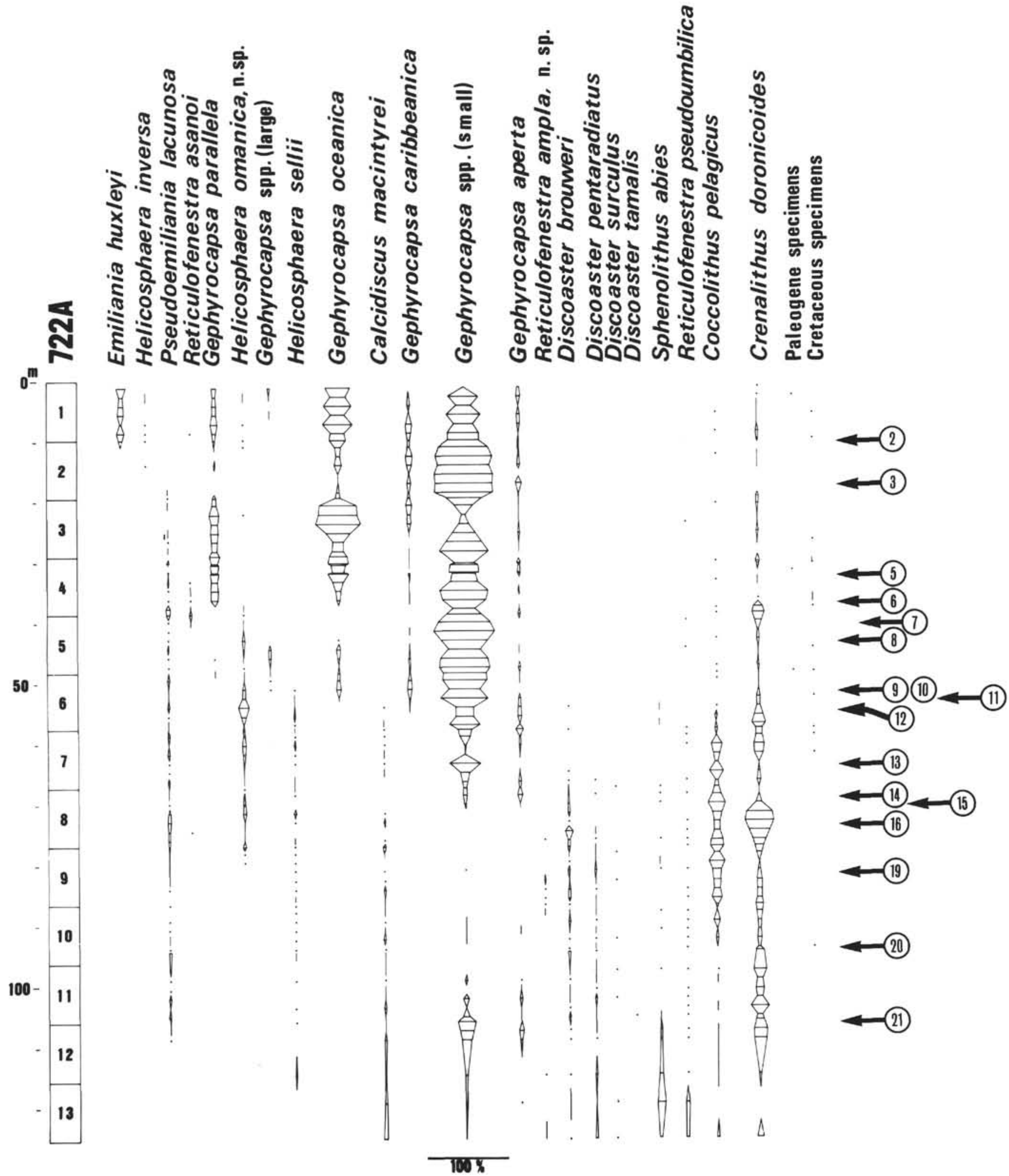

Figure 8. Stratigraphic distribution and relative abundance of selected calcareous nannofossil species in Hole 722A, ODP Leg 117.

placed between Samples 117-722A-1H-CC and 117-722A-2H-1, 115–117 cm. Datum 3 (LAD *Pseudoemiliania lacunosa*) is recognized between Samples 117-722A-2H-5, 115–117 cm, and 117-722A-2H-6, 115–117 cm. Samples between Datums 2 and 3 contain fairly abundant specimens of small *Gephyrocapsa* which form more than 50% of the total flora. Below Datum 3, Samples 117-722A-3H-1, 115–117 cm, through 117-722A-3H-3, 115–117 cm, contain fairly abundant *Gephyrocapsa oceanica*. The interval represented by six samples (Sample 117-722A-4H-3, 115–117 cm, through Sample 117-722A-5H-1, 115–117 cm) is characterized by occurrences of *Reticulofenestra asanoi*. Therefore, Datum 5 (LAD *Reticulofenestra asanoi*) and Datum 7 (bottom of acme of *Reticulofenestra asanoi*) are placed between Samples 117-722A-4H-2, 118–119 cm, and 117-722A-4H-3, 115–117 cm, and Samples 117-722A-5H-1, 115–117 cm, and 117-722A-5H-2, 115–117 cm, respectively. As in the upper three samples in this interval, *Reticulofenestra asanoi* occurs together with *Gephyrocapsa parallela*, Datum 6 (FAD *Gephyrocapsa parallela*) is detected between Samples 117-722A-4H-5, 115–117 cm, and 117-722A-4H-6, 115–117 cm. *Pseudoemiliania lacunosa* is comparatively abundant in Samples 117-722A-4H-6, 115–117 cm, and 117-722A-4H-CC. *Helicosphaera omanica*, n. sp. is continuously present below Datum 6. *Gephyrocapsa* specimens larger than 6 μm are concentrated in Samples 117-722A-5H-4, 115–117 cm, down to 117-722A-6H-2, 115–117 cm. *Helicosphaera sellii* is abundant below Sample 117-722A-6H-3, 115–117 cm. Therefore, Datum 8 (LAD large *Gephyrocapsa*) is placed between Samples 117-722A-5H-3, 115-117 cm and 117-722A-5H-4, 115–117 cm. Datums 9 and 10 (LAD *Helicosphaera sellii* and FAD large *Gephyrocapsa*) are between Samples 117-722A-6H-2, 115–117 cm, and 117-722A-6H-3, 115–117 cm. This suggests that Pleistocene sediments between Datums 9 and 10 may be missing or very thin. The interval between Datums 6 and 8 is characterized by the near absence of *Gephyrocapsa caribbeanica* and *G. oceanica* and the abundant occurrences of small *Gephyrocapsa* and *Crenalithus doronicoides*. *Gephyrocapsa oceanica* is present above Sample 117-722A-6H-3, 115–117 cm, and *Calcidiscus macintyrei* below Sample 117-722A-6H-4, 115–117 cm. This horizon is Datum 11 (LAD *Calcidiscus macintyrei* and FAD *Gephyrocapsa oceanica*). Sample 117-722A-6H-4, 115–117 cm, is the lowest sample which contains *Gephyrocapsa caribbeanica*. Therefore Datum 12 (FAD *Gephyrocapsa caribbeanica*) is just below this sample. *Helicosphaera omanica*, n. sp. is comparatively abundant between Datums 11 and 12.

Calcareous nannofossil assemblages of the Pliocene and upper Miocene at this site are similar to those of Site 721. Datum 13 (LAD *Discoaster brouweri*) is recognized between Samples 117-722A-7H-4, 114–116 cm, and 117-722A-7H-5, 115–117 cm. Samples 117-722A-7H-5, 115–117 cm, and 117-722A-8H-1, 115–117 cm, contain abundant small *Gephyrocapsa*. This category, however, rapidly decreases in number in Sample 117-722A-8H-2, 115–117 cm, and is rare below this sample. Consequently, Datum 14 (bottom of acme of *Gephyrocapsa*) is placed between Samples 117-722A-8H-1, 115–117 cm, and 117-722A-8H-2, 115–117 cm. A large number of *Crenalithus doronicoides* occurs in Samples 117-722A-8H-3, 115–117 cm, through 117-722A-8H-CC. Some specimens are comparatively large. Therefore, Datum 15 (top of "upper acme" of *Crenalithus doronicoides*) is placed between Samples 117-722A-8H-2, 115–117 cm, and 117-722A-8H-3, 115–117 cm. *Discoaster pentaradiatus* occurs continuously in and below Sample 117-722A-8H-5, 115–117 cm. Therefore, Datum 16 (LAD *Discoaster pentaradiatus*) is recognized between Samples 117-722A-8H-4, 114–116 cm, and 117-722A-8H-5, 115–117 cm. In this hole, the last occurrences of *Discoaster surculus* and *D. tamalis* (Datums 17 and 18) cannot be detected because these species are very rare or absent. The lowest occurrence of *Helicosphaera omanica*, n. sp. is found in Sample 117-722A-9H-2, 115–117 cm. *Reticulofenestra ampla*, n. sp. is present in and below Sample 117-722A-9H-4, 115–117 cm, and, therefore, Datum 19 (LAD *Reticulofenestra ampla*) is placed between Samples 117-722A-9H-3, 103–105 cm, and 117-722A-9H-4, 115–117 cm. Furthermore, *Crenalithus doronicoides* increases in number again below Sample 117-722A-10X-CC. Therefore, Datum 20 (top of "lower acme" of *Crenalithus doronicoides*) is detected between Samples 117-722A-10X-5, 123–125 cm, and 117-722A-10X-CC. Some specimens of *Crenalithus doronicoides* in Samples 117-722A-10X-CC and 117-722A-11X-1, 115–117 cm, are relatively large, and occasionally reach a size of over 6 μm in diameter.

The last occurrence of *Sphenolithus abies* is recognized between Samples 117-722A-11X-5, 115–117 cm, and 117-722A-11X-6, 115–117 cm. The sporadic occurrences of *Reticulofenestra pseudoumbilica* are recognized throughout this hole. However, abundant and continuous occurrences of this species are found below Sample 117-722A-12X-1, 116–118 cm. Consequently, Datum 21 (LAD *Reticulofenestra pseudoumbilica*) is placed between Samples 117-722A-11X-CC and 117-722A-12X-1, 116–118 cm. Specimens above this datum are considered to be reworked. This datum is placed slightly below the top of *Sphenolithus abies*. Abundant occurrences of small *Gephyrocapsa* are recognized from Samples 117-722A-11X-2, 115–117 cm, down to 117-722A-12X-2, 114–116 cm.

The following species are dominant below Sample 117-722A-12X-1, 116–118 cm: *Calcidiscus leptoporus*, *C. macintyrei*, *Crenalithus doronicoides*, *Reticulofenestra pseudoumbilica*, and *Sphenolithus abies*. The interval represented by Samples 117-722A-12X-1, 116–118 cm, through 117-722A-17X-CC contains few age-diagnostic species. Therefore, this interval is tentatively correlated to NN15–NN12. Sediments below Sample 117-722A-18X-1, 115–117 cm, contain *Discoaster quinqueramus* and *D. berggreni*. The boundary between NN12 and NN11 is recognized between Samples 117-722A-17X-CC and 117-722A-18X-1, 115–117 cm. Fewer reworked Paleogene and Cretaceous specimens are found in this hole than in Site 721.

Hole 722B

Sample 117-722B-29X-CC contains *Discoaster quinqueramus* together with *D. berggreni* and is assigned to NN11. Samples 117-722B-30X-CC through 117-722B-32X-CC contain neither *Discoaster quinqueramus* nor *D. hamatus*, and are assigned to NN10. There is a remarkable change in the species composition between Samples 117-722B-30X-CC and 117-722B-31X-CC. Sediments above Sample 117-722B-30X-CC contain abundant small placoliths such as *Dictyococcites* cf. *productus*, whereas sediments below Sample 117-722B-31X-CC are dominated by large-sized placoliths such as *Reticulofenestra gelida* and *R. pseudoumbilica*. Samples 117-722B-33X-1, 115–116 cm, through 117-722B-34X-CC are characterized by continuous occurrences of *Discoaster hamatus* together with a few specimens of *Catinaster coalitus*, *Discoaster calcaris*, and *D. neohamatus*. Therefore, these samples belong to NN9. The interval represented by Samples 117-722B-35X-CC through 117-722B-40X-2, 110–111 cm, is characterized by the absence of *Discoaster hamatus* and *Cyclicargolithus floridanus*. The lower part of this interval (Samples 117-722B-37X-CC through 117-722B-40X-2, 110–111 cm) contains *Discoaster kugleri*. This interval is referred to NN8 and NN7. As was seen at the previous site, however, both *Discoaster hamatus* and *Catinaster coalitus* first occur in the same sample in this hole (Sample 117-722B-34X-CC). Because of this, we cannot define the NN8/NN7 boundary clearly. The presence of *Cyclicargolithus floridanus* and the absence of *Discoaster kugleri* in Sample 117-722B-40X-CC suggests that this sample belong to NN6.

The preservation of nannofossils becomes poor in Sample 117-722B-41X-2, 32–33 cm, and remains poor to the bottom of the hole. Asteroliths and sphenoliths are heavily overgrown and the coccoliths have undergone varying degrees of dissolution. As a result, the biostratigraphy of this part of the hole becomes dubious. Samples 117-722B-41X-2, 32–33 cm, through 117-722B-46X-2, 115–116 cm, may belong to NN5 and NN4 because of the continuous occurrence of *Sphenolithus heteromorphus*. Sample 117-722B-46X-CC contains no age-diagnostic species. Samples 117-722B-48X-CC through 117-722B-57X-CC are barren or have such small quantities of nannofossils that they should be considered barren, with the exception of Sample 117-722B-52X-4, 115–116 cm. This sample contains comparatively abundant but no age-diagnostic species. *Sphenolithus belemnos* occurs in Sample 117-722B-58X-5, 7–8 cm. Therefore, this sample may belong to NN3. In the lowermost two samples of this hole, the nannofossils are present in low concentration.

Site 731 (Table 6, Fig. 9)

Site 731 is located just below the crest of the Owen Ridge in the western Arabian Sea, about 6 km south of DSDP Site 224. This site penetrated to 994.2 meters below seafloor (mbsf) and recovered sediments that range from Holocene to possible Oligocene (NP25).

Hole 731A

Helicosphaera inversa first occurs in Sample 117-731A-1H-5, 115–117 cm, and Datum 1 (LAD *Helicosphaera inversa*) is placed between Samples 117-731A-1H-4, 115–117 cm, and 117-731A-1H-5, 115–117 cm. Unfortunately, *H. inversa* is very rare and the stratigraphic position of Datum 1 has low confidence. Datum 2 (FAD *Emiliania huxleyi*) is placed between Samples 117-731A-1H-CC and 117-731A-2H-1, 115–117 cm. Above this datum typical *Emiliania huxleyi* occur. The sediments above Datum 2 also contain abundant *Gephyrocapsa oceanica*, and *G. aperta* is comparatively abundant. *Pseudoemiliania lacunosa* first occurs in Sample 117-731A-2H-CC and Datum 3 (LAD *Pseudoemiliania lacunosa*) is detected between this sample and Sample 117-731A-2H-6, 115–117 cm. The sediments between Datums 2 and 3 contain fairly abundant small *Gephyrocapsa* specimens, whereas *G. oceanica* is very rare or absent. *Reticulofenestra asanoi* occurs continuously in Samples 117-731A-5H-3, 115–117 cm, through 117-731A-5H-CC. Therefore, Datums 5 (LAD *Reticulofenestra asanoi*) and 7 (bottom of acme of *Reticulofenestra asanoi*) are placed between Samples 117-731A-5H-2, 115–117 cm, and 117-731A-5H-3, 115–117 cm, and between Samples 117-731A-5H-CC and 117-731A-6H-1, 115–117 cm, respectively. Sporadic occurrences of *R. asanoi* above Datum 5 may be reworked. Many samples between Datums 3 and 5 contain comparatively abundant *Gephyrocapsa parallela*. *Gephyrocapsa parallela* is found only in the interval above Sample 117-731A-5H-4, 115–117 cm. Therefore, Datum 6 (FAD *Gephyrocapsa parallela*) is placed between Samples 117-731A-5H-4, 115–117 cm, and 117-731A-5H-5, 115–117 cm. As was the case in the previous hole, *Helicosphaera omanica*, n. sp. occurs almost continuously below Datum 6. Abundant occurrences of large *Gephyrocapsa* are recognized below Sample 117-731A-6H-4, 115–117 cm, so Datum 8 (LAD large *Gephyrocapsa*) is detected between Samples 117-731A-6H-3, 115–117 cm, and 117-731A-6H-4, 115–117 cm. *Gephyrocapsa oceanica* and *G. caribbeanica* are absent or very rare in the sediments between Datums 5 and 8. *Helicosphaera sellii* is found as high as Sample 117-731A-7H-3, 115–117 cm. Large *Gephyrocapsa* continuously occur down to Sample 117-731A-7H-2, 115–117 cm. Therefore, both Datum 9 (LAD *Helicosphaera sellii*) and Datum 10 (FAD large *Gephyrocapsa*) are placed in the same interval: between Samples 117-731A-7H-2, 115–117 cm, and 117-731A-7H-3, 115–117 cm. This suggests that sediments ranging from Datum 9 to Datum 10 are very thin or completely missing. Except for Sample 117-731A-9X-3, 115–117 cm, *Gephyrocapsa oceanica* and *G. caribbeanica* do not occur below Samples 117-731A-7H-CC and 117-731A-8X-1, 115–117 cm, respectively. Therefore, Datum 11 (LAD *Calcidiscus macintyrei* and FAD *Gephyrocapsa oceanica*) and Datum 12 (FAD *Gephyrocapsa caribbeanica*) are placed between Samples 117-731A-7H-6, 115-117 cm and 117-731A-7H-CC and between Samples 117-731A-7H-CC and 117-731A-8X-1, 115–117 cm, respectively. In contrast to previous holes, *Calcidiscus macintyrei* is found slightly above Datum 11. *Coccolithus pelagicus* becomes dominant below Datum 12.

Pliocene to upper Miocene nannofossil floras at Site 731 are characterized by fewer species than at Sites 721 and 722. Throughout the section ranging from Samples 117-731A-8X-1, 115–117 cm, down to 117-731A-11X-1, 115–117 cm, *Calcidiscus leptoporus, Coccolithus pelagicus*, and *Crenalithus doronicoides* commonly occur. Some *Discoaster* species are also present.

Discoaster brouweri occurs continuously in and below Sample 117-731A-9X-CC. Although a single specimens of this species is present in Sample 117-731A-9X-4, 115–117 cm, it seems to be reworked. Therefore, Datum 13 (LAD *Discoaster brouweri*) is tentatively placed between Samples 117-731A-9X-5, 115–117 cm and 117-731A-9X-CC. Small *Gephyrocapsa* specimens are relatively abundant in and above Sample 117-731A-10X-2, 115–117 cm. Consequently, Datum 14 (bottom of acme of *Gephyrocapsa*) is clearly recognized between Samples 117-731A-10X-2, 115–117 cm, and 117-731A-10X-3, 115–117 cm. *Crenalithus doronicoides* is abundant in and below Sample 117-731A-10X-4, 115–117 cm, with the diameters of some specimens greater than 6 μm. Therefore, Datum 15 (top of "upper acme" of *Crenalithus doronicoides*) is placed in the interval between Samples 117-731A-10X-3, 115–117 cm, and 117-731A-10X-4, 115–117 cm. *Reticulofenestra asanoi* is found in both Samples 117-731A-10X-4, 115–117 cm, and 117-731A-10X-5, 115–117 cm. Because of the presence of *Discoaster pentaradiatus* in and below Sample 117-731A-10X-CC, Datum 16 (LAD *Discoaster pentaradiatus*) is situated between Samples 117-731A-10X-6, 115–117 cm, and 117-731A-10X-CC.

Nannofossil assemblages change between Samples 117-731A-11X-1, 115–117 cm, and 117-731A-11X-2, 116–118 cm. *Reticulofenestra pseudoumbilica* and *Sphenolithus abies* are continuously found in and below Sample 117-731A-11X-2, 116–118 cm. Therefore, Datum 21 (LAD *Reticulofenestra pseudoumbilica*) seems to be placed between Samples 117-731A-11X-1, 115–117 cm, and 117-731A-11X-2, 116–118 cm. Datums 19 (LAD *Reticulofenestra ampla*) and 20 (top of "lower acme" of *Crenalithus doronicoides*) are not recognized in this hole. The lowest occurrence of *Helicosphaera omanica*, n. sp. was found just above Datum 17 (LAD *Discoaster surculus*) at Site 721. This species, however, occurs continuously down to Sample 117-731A-11X-1, 115–117 cm, at this site. Therefore, the sediments ranging from Datum 17 to Datum 21 are probably missing.

As mentioned above, the presence of *Reticulofenestra pseudoumbilica* is recognized in and below Sample 117-731A-11X-2, 116–118 cm. However, because of the absence of some important zonal markers for the early Pliocene such as *Amaurolithus tricorniculatus, Ceratolithus rugosus*, and *Discoaster asymmetricus*, sediments from Samples 117-731A-11X-2, 116–118 cm, down to 117-731A-12X-5, 115–117 cm, are tentatively assigned to NN15 to NN12.

Samples 117-731A-12X-6, 115–117 cm, through 117-731A-17X-CC contain *Discoaster quinqueramus* together with *D. berggreni* and are assigned to NN11. A diverse assemblage of discoasters is found in this zone which in addition to *Discoaster quinqueramus* and *D. berggreni*, include: *D. adamanteus, D. bellus, D. brouweri, D. challengeri, D. decorus, D. deflandrei, D. in-*

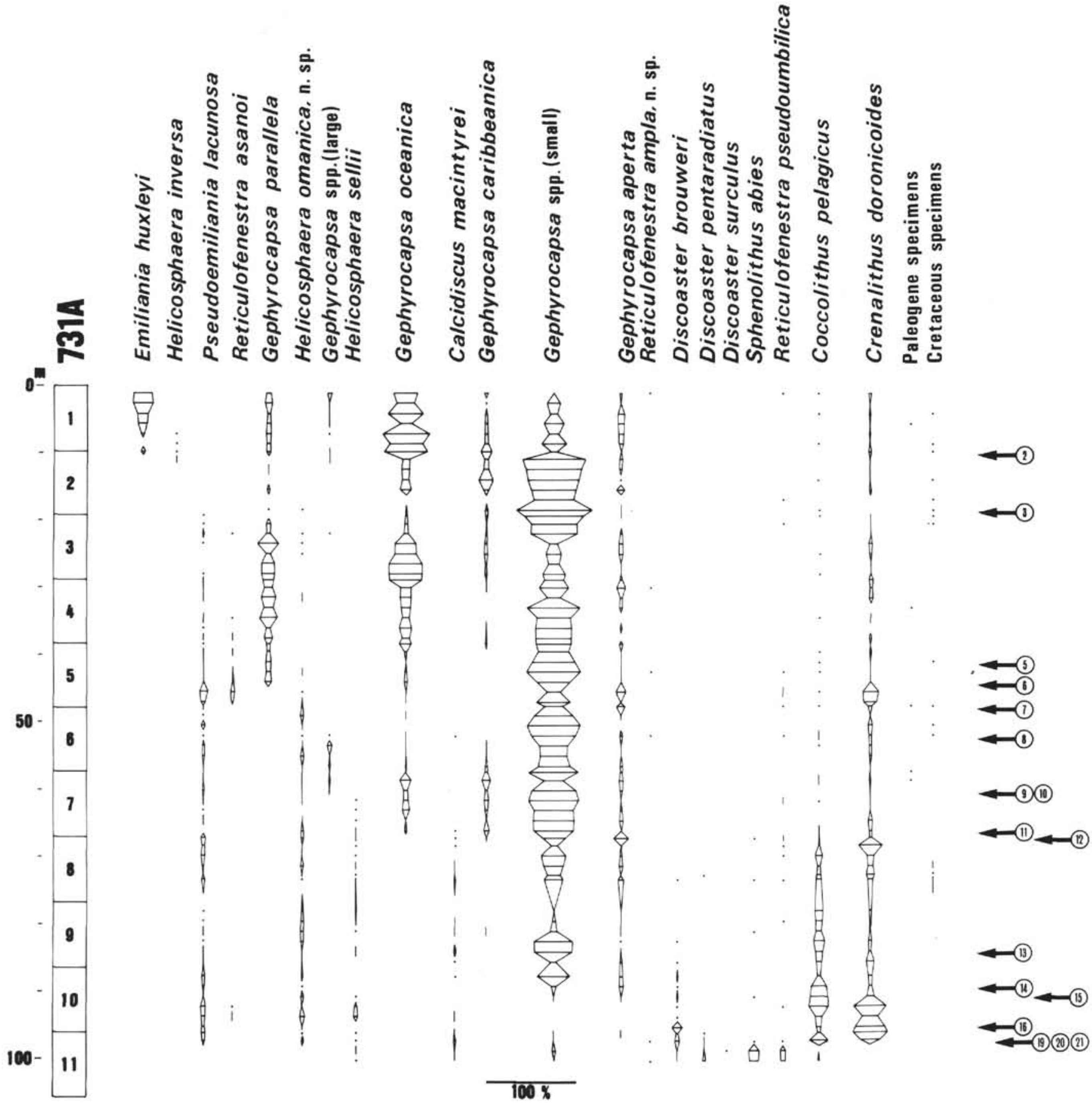

Figure 9. Stratigraphic distribution and relative abundance of selected calcareous nannofossil species in Hole 731A, ODP Leg 117.

tercalaris, D neohamatus, D. pansus, D. pentaradiatus, D. perclarus, D. pseudovariabilis, D. surculus, D. triradiatus, and *D. variabilis.* Nannofossils are abundant with moderate preservation throughout this zone. Neither *Discoaster hamatus* nor *D. quinqueramus* was found in Samples 117-731A-18X-1, 135–137 cm, through 117-731A-21X-CC so this interval can be assigned to upper Miocene NN10. Nannofossils are abundant, and the preservation ranges from good in the upper part to moderate in the lower part of this zone. As we have seen in previous holes, a change in the floral composition is recognized between Samples 117-731A-19X-2, 115–117 cm, and 117-731A-19X-CC. Small placoliths such as *Crenalithus* cf. *doronicoides* and *Dictyococcites* cf. *productus* comprise more than 80% above this sample. Large placoliths such as *Reticulofenestra gelida* and *R. pseudoumbilica* are dominant below this sample. *Discoaster hamatus* is present in Samples 117-731A-22X-2, 111–113 cm, through 117-731A-25X-CC. This interval is assigned to NN9. *Discoaster neohamatus* and *Catinaster coalitus* occur in the upper and the lower part of this zone, respectively. Samples 117-731A-26X-3, 117–119 cm, through 117-731A-29X-CC are assigned to NN8 and NN7, because these samples lack *Discoaster hamatus* and because Samples 117-731A-27X-CC, 117-731A-28X-CC, and 117-

731A-29X-CC contain a few specimens of *Discoaster kugleri*. Like *Discoaster hamatus, Catinaster coalitus* is present in and above Sample 117-731A-25X-CC. Consequently, the NN7/NN8 boundary is not clear.

The state of preservation becomes poor, with heavy overgrowth in Samples 117-731A-30X-CC through 117-731A-33X-CC. Samples 117-731A-30X-CC and 117-731A-31X-1, 115–116 cm, contain *Cyclicargolithus floridanus*, whereas *Reticulofenestra gelida* and *R. pseudoumbilica* are rare in these samples.

Samples 117-731A-31X-CC through 117-731A-43X-4, 105–106 cm, contain *Sphenolithus heteromorphus. Helicosphaera ampliaperta*, whose LAD is used to define the top of NN4, is not present in this region and so it is necessary to combine NN5 and NN4. In this interval, calcareous nannofossils are rare or barren in Samples 117-731A-35X-CC and 117-731A-36X-CC, and Samples 117-731A-39X-2, 81–82 cm, through 117-731A-42X-CC. In Sample 117-731A-38X-CC reworked Paleogene species are common. These include: *Chiasmolithus altus, Cyclicargolithus abisectus, Discoaster barbadiensis, Helicosphaera recta, Sphenolithus capricornutus, S. ciperoensis, S. conicus*, and *S. predistentus*. Sample 117-731A-43X-CC, which is the deepest sample from this hole, contains abundant, poorly preserved nannofossils including *Sphenolithus belemnos* and *Discoaster druggii*, and can be placed in lower Miocene NN3. Drilling in Hole 731A stopped at a depth of 409.9 mbsf due to mechanical problems.

Hole 731B

Coring at Hole 731B commenced at 408.7 mbsf after the overlying section had been drilled and washed. Only five XCB cores were recovered from this hole before it, too, was abandoned because of mechanical problems. All five core-catcher samples are barren of nannofossils.

Hole 731C

Hole 731C was drilled down to a depth of 351.7 mbsf. At this point, washing commenced and continued to 502.4 mbsf. Sample 117-731C-1W-CC contains *Sphenolithus belemnos* and *S. heteromorphus* together with abundant *Crenalithus* cf. *doronicoides*. A rotary core was taken immediately below the washed core. Sample 117-731C-2R-2, 38–39 cm, contains *Sphenolithus belemnos* and *S. heteromorphus* together with abundant *Cyclicargolithus floridanus*. Sample 117-731C-2R-CC contains only a few calcareous nannofossils including *Sphenolithus belemnos*. Washing of the hole continued from 512.1 to 560.1 mbsf. Within this interval, Sample 117-731C-3W-2, 78–79 cm, was found to contain *Sphenolithus belemnos, S. moriformis*, and *Cyclicargolithus floridanus*. The nannofossil assemblages in Samples 117-731C-1W-CC through 117-731C-3W-2, 78–79 cm, as mentioned above, place these samples in the early Miocene (NN3–NN2). Sample 117-731C-3W-CC contains rare nannofossils with moderate to poor preservation. Age-diagnostic taxa are not recognizable. Core 117-731C-4R was taken immediately below the washed interval, but the core catcher was barren of nannofossils. Hole 731C was washed from 569.9 to 618.1 mbsf. The core catcher of Core 117-731C-5W contains no calcareous nannofossils. Core 117-731C-6R was taken immediately below the washed interval. Sample 117-731C-6R-CC is also barren of nannofossils. Core 117-731C-7W is from the washed interval between 627.8 and 675.9 mbsf. An abundant but poorly preserved nannoflora is contained in Sample 117-731C-7W-2, 83–84 cm. This flora is composed of very abundant *Discoaster deflandrei* and *Cyclicargolithus floridanus* but no age-diagnostic forms. The age of this sample is therefore uncertain. Core 117-731C-8R was taken immediately below the washed interval. Sample 117-731C-8R-3, 32–33 cm, contains fairly abundant calcareous nannofossils such as *Coccolithus pelagicus, Crenalithus* cf. *doronicoides, Cyclicargolithus floridanus, Discoaster deflandrei*, and *Sphenolithus moriformis*. Age-diagnostic taxa are, however, not recognizable. Below this, sediments down to the bottom of the hole are all barren or have so few nannofossils that they should be considered barren. The one and only brief flicker of hope was in Sample 117-731C-13W-5, 73–74 cm. An abundant, yet moderately preserved, nannofossil assemblage which includes *Coccolithus eopelagicus, C. pelagicus, Cyclicargolithus floridanus, Dictyococcites bisectus, Discoaster deflandrei, Helicosphaera recta*, and *Sphenolithus ciperoensis* was recognized. A zonal assignment of NP25 (upper Oligocene) has been given to this sample.

DESCRIPTION OF NEW SPECIES

Genus HELICOSPHAERA Kamptner, 1954

Helicosphaera omanica Sato, Kameo and Takayama, n. sp.
(Plate 1, figs. 1-3)

Description. Species having relatively large, thick shields appressed into a compact form of somewhat egg shape with helicoid rim. The central area contains a relatively large rectangular slit or triangular opening.

Remarks. *Helicosphaera omanica* is distinguished from the usually associated *Helicosphaera carteri* by having a large rectangular slit or triangular opening, somewhat egg shaped outline and relatively large and thick shields. This new species also easily distinguishable from *Helicosphaera sellii* by having the central opening without a bar.

Size. About 15 μm.

Occurrence. *Helicosphaera omanica* occurs in the upper Pliocene and the lower Pleistocene in the deep-sea sediments of the Arabian Sea, Indian Ocean. The last appearance of this species corresponds to Datum 6 (FAD *Gephyrocapsa parallela*) in this area.

Holotype. TOCCN 16952(1) (Pl. 1, figs. la, b).

Paratypes. TOCCN 16952(2) and (3) (Pl. 1, figs. 2 and 3).

Type locality. Arabian Sea, Indian Ocean, ODP Leg 117, Hole 721A, Sample 117-721A-4H-3, 115–117 cm.

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Genus RETICULOFENESTRA Hay et al., 1966

Reticulofenestra ampla Sato, Kameo and Takayama, n. sp.
(Plate 1, figs. 4–6)

Description. This species is an elliptical placolith with a narrow and oval central opening. The shields have relatively distinct outlines and are characterized by weak birefringence. The distal shield is as large as or slightly larger than the proximal one. The elements of each shield are slightly imbricate or nonimbricate. In cross-polarized light the central collar looks very thin in comparison with the width of the shield. It seems to be an "elongate and oval" small *Reticulofenestra* under the light microscope.

Remarks. In cross-polarizing light, *Reticulofenestra ampla* closely resembles *R. pseudoumbilica* and *R. gelida* which occur in upper Cenozoic sequences. However, it differs from *R. pseudoumbilica* by its smaller size, more elongate shape, narrower central opening, thinner central collar, and weaker birefringence of the shield. Although *R. ampla* is similar to *R. gelida* in having a narrow central opening, it is distinguished from *R. gelida* by its consistently smaller size and by considerably weaker brightness than *R. gelida*. Haq and Berggren (1978) refer to small forms (4–6 μm) similar to *R. pseudoumbilica* as *Reticulofenestra* sp. These have a small central pore (or opening) with a very thin collar around it. Probably, *R. ampla* is the same species as *Reticulofenestra* sp. of Haq and Berggren.

Occurrence. This species occurs in the Miocene through lowermost upper Pliocene sediments at the North Atlantic Ocean and the Indian Ocean. *Reticulofenestra ampla* is abundant just above the top of *R. pseudoumbilica* and increase upward. However, this species suddenly goes extinct slightly below the top of *Discoaster tamalis*, the boundary between Zone CN12a *(Discoaster tamalis* Subzone) and CN12b *(Discoaster surculus* Subzone) of the zonal scheme of Okada and Bukry (1980).

Holotype. TOCCN 16954(1) (Pl. 1, figs. 4a, b).

Paratypes. TOCCN 16953 and TOCCN 16954(2) (Pl. 1, figs. 5, 6).

Type locality. Atlantic Ocean, DSDP Leg 94, Hole 607, Sample 13H-CC.

Depository. Technical Research Center, Teikoku Oil Co., Ltd., Tokyo, Japan.

FLORAL REFERENCE LIST

Thirty genera and 117 species were recognized during this investigation, including two new species. The species are listed below and brief remarks are added to some. Bibliographic references of previously described species may be found by consulting Loeblich and Tappan (1966–1973), Farinacci (1976–1988), van Heck (1979–1983), Steinmetz (1984–1986), Takayama and Sato (1987), and Sato and Takayama (1990).

Amaurolithus primus (Bukry and Percival) Gartner and Bukry, 1975
Braarudosphaera bigelowi (Gran and Braarud) Deflandre, 1947
Calcidiscus leptoporus (Murray and Blackman) Loeblich and Tappan, 1978
Calcidiscus macintyrei (Bukry and Bramlette) Loeblich and Tappan, 1978
Calcidiscus premacintyrei Theodoridis, 1984
Catinaster calyculus Martini and Bramlette, 1963
Catinaster coalitus Martini and Bramlette, 1963
Catinaster mexicanus Bukry, 1971
Ceratolithus acutus Gartner and Bukry, 1974
Ceratolithus cristatus Kamptner, 1950
Ceratolithus rugosus Bukry and Bramlette, 1968
Ceratolithus simplex Bukry, 1979
Ceratolithus telesmus Norris, 1965
Coccolithus eopelagicus (Bramlette and Riedel) Bramlette and Sullivan, 1961
Coccolithus miopelagicus Bukry, 1971
Coccolithus pelagicus (Wallich) Schiller, 1930
Coccolithus streckeri Takayama and Sato, 1987
Coccolithus subdistichus (Roth and Hay) Bukry and Bramlette, 1970
Coronocyclus nitescens (Kamptner) Bramlette and Wilcoxon, 1967
Coronocyclus serratus Hay, Mohler and Wade, 1966
Crenalithus doronicoides (Black and Barnes) Roth, 1973
Cyclicargolithus abisectus (Müller) Bukry, 1973
Cyclicargolithus floridanus (Roth and Hay) Bukry, 1971
Cyclolithella annula (Cohen) McIntyre and Bé, 1967
Dictyococcites antarcticus Haq, 1976
Dictyococcites bisectus (Hay, Mohler and Wade) Bukry and Percival, 1971
Dictyococcites productus (Kamptner) Backman, 1980
Discoaster adamanteus Bramlette and Wilcoxon, 1967
Discoaster asymmetricus Gartner, 1969
Discoaster aulakos Gartner, 1967
Discoaster barbadiensis Tan Sin Hok, 1927
Discoaster bellus Bukry, 1971
Discoaster berggreni Bukry, 1971
Discoaster bollii Martini and Bramlette, 1963
Discoaster braarudi Bukry, 1971
Discoaster brouweri Tan Sin Hok, 1927
Discoaster calcaris Gartner, 1967
Discoaster calculosus Bukry, 1971
Discoaster challengeri Bramlette and Riedel, 1954
Discoaster decorus (Bukry) Bukry, 1973
Discoaster deflandrei Bramlette and Riedel, 1954
Discoaster druggii Bramlette and Wilcoxon, 1967
Discoaster exilis Martini and Bramlette, 1963
Discoaster formosus Martini and Worsley, 1971
Discoaster hamatus Martini and Bramlette, 1963
Discoaster intercalaris Bukry, 1971
Discoaster kugleri Martini and Bramlette, 1963
Discoaster neohamatus Bukry and Bramlette, 1969
Discoaster neorectus Bukry, 1971
Discoaster nephados Hay, 1967
Discoaster pansus (Bukry and Percival) Bukry, 1973
Discoaster pentaradiatus Tan Sin Hok, 1927
Discoaster perclarus Hay, 1967
Discoaster petaliformis Moshkovitz and Ehrich, 1980
Discoaster prepentaradiatus Bukry and Percival, 1971
Discoaster pseudovariabilis Martini and Worsley, 1971
Discoaster quadramus Bukry, 1973
Discoaster quinqueramus Gartner, 1969
Discoaster signus Bukry, 1971
Discoaster surculus Martini and Bramlette, 1963
Discoaster tamalis Kamptner, 1967
Discoaster triradiatus Tan Sin Hok, 1927
Discoaster tristellifer Bukry, 1976
Discoaster variabilis Martini and Bramlette, 1963
Discolithina japonica Takayama, 1967
Discolithina macropora (Deflandre) Levin and Joerger, 1967
Discolithina multipora (Kamptner ex Deflandre) Martini, 1965
Emiliania huxleyi (Lohman) Hay and Mohler, 1967
Geminilithella jafari (Müller) Backman, 1980
Geminilithella rotula (Kamptner) Backman, 1980
Gephyrocapsa aperta Kamptner, 1963
Gephyrocapsa caribbeanica Boudreaux and Hay, 1967 (Remarks: Calcareous nannofossil assemblages in Pleistocene to Holocene sequences are characterized by the dominance of *Gephyrocapsa*. Most of these *Gephyrocapsa* are smaller than 4 μm. In our study, *Gephyrocapsa caribbeanica* was identified by characteristics features such as the size (larger than 4 μm) and orientation of the diagonal bar (greater than 45° angle with the short axis). Specimens which are larger than 6 μm were put in "large *Gephyrocapsa caribbeanica*.")
Gephyrocapsa oceanica Kamptner, 1943 (Remarks: *Gephyrocapsa oceanica* was identified by size (larger than 4 μm) and orientation of the diagonal bar (less than 45° angle with short axis). Specimens which are larger than 6 μm were put in "large *Gephyrocapsa oceanica*.")
Gephyrocapsa parallela Hay and Beaudry, 1973
Gephyrocapsa sinuosa Hay and Beaudry, 1973
Hayaster perplexus (Bramlette and Riedel) Bukry, 1973
Helicosphaera carteri (Wallich) Kamptner, 1954
Helicosphaera euphratis Haq, 1966
Helicosphaera granulata (Bukry and Percival) Jafar and Martini, 1975
Helicosphaera hyalina Gaarder, 1970
Helicosphaera inversa (Gartner) Theodoridis, 1984
Helicosphaera mediterranea Müller, 1981
Helicosphaera neogranulata (Gartner) Haq and Berggren, 1978
Helicosphaera obliqua Bramlette and Wilcoxon, 1967
Helicosphaera omanica Sato, Kameo and Takayama, n. sp.
Helicosphaera orientalis Black, 1971
Helicosphaera recta Haq, 1966
Helicosphaera sellii (Bukry and Bramlette) Jafar and Martini, 1975
Helicosphaera wallichi (Lohmann) Okada and McIntyre, 1977
Oolithotus antillarum (Cohen) Reinhardt, 1968
Pontosphaera discopora Schiller, 1925
Reticulofenestra ampla Sato, Kameo and Takayama, n. sp.
Reticulofenestra asanoi Sato and Takayama, 1990
Reticulofenestra gelida (Geitznauer) Backman, 1978
Reticulofenestra pseudoumbilica (Gartner) Gartner, 1969
Rhabdosphaera clavigera Murray and Blackman, 1898
Rhabdosphaera longistylis Schiller, 1925
Rhabdosphaera stylifera Lohmann, 1902
Scapholithus fossilis Deflandre, 1954
Scyphosphaera sp.
Sphenolithus abies Deflandre, 1953
Sphenolithus belemnos Bramlette and Wilcoxon, 1967
Sphenolithus ciperoensis Bramlette and Wilcoxon, 1967
Sphenolithus conicus Bukry, 1971
Sphenolithus dissimilis Bukry and Percival, 1971
Sphenolithus distentus (Martini) Bramlette and Wilcoxon, 1967
Sphenolithus heteromorphus Deflandre, 1953
Sphenolithus moriformis (Brönniman and Stradner) Bramlette and Wilcoxon, 1967
Sphenolithus predistentus Bramlette and Wilcoxon, 1967
Syracosphaera pulchra Lohmann, 1902
Thoracosphaera deflandrei Kamptner, 1956
Thoracosphaera heimi (Lohmann) Kamptner, 1954
Thoracosphaera saxea Stradner, 1961
Triquetrorhabdulus carinatus Martini, 1965
Triquetrorhabdulus rugosus Bramlette and Wilcoxon, 1967
Umbellosphaera irregularis Paasche, 1955
Umbilicosphaera mirabilis Lohmann, 1902

ACKNOWLEDGMENTS

We are grateful to many of the scientific staff on board the *JOIDES RESOLUTION*. Deep appreciation is expressed to Drs. Naomoto Komatsu, Yoshiro Kikuchi, Yoshihiko Fujita, and Stacia Spaulding for their help and encouragement. We thank Mrs. Yukie Sato and Miss Kyoko Kodama for assistance in table preparation, bookkeeping of samples, and sample preparations. We are especially grateful to anonymous reviewers for reading an earlier draft of this manuscript.

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Date of initial receipt: 26 September 1989
Date of acceptance: 13 July 1990
Ms 117B-133

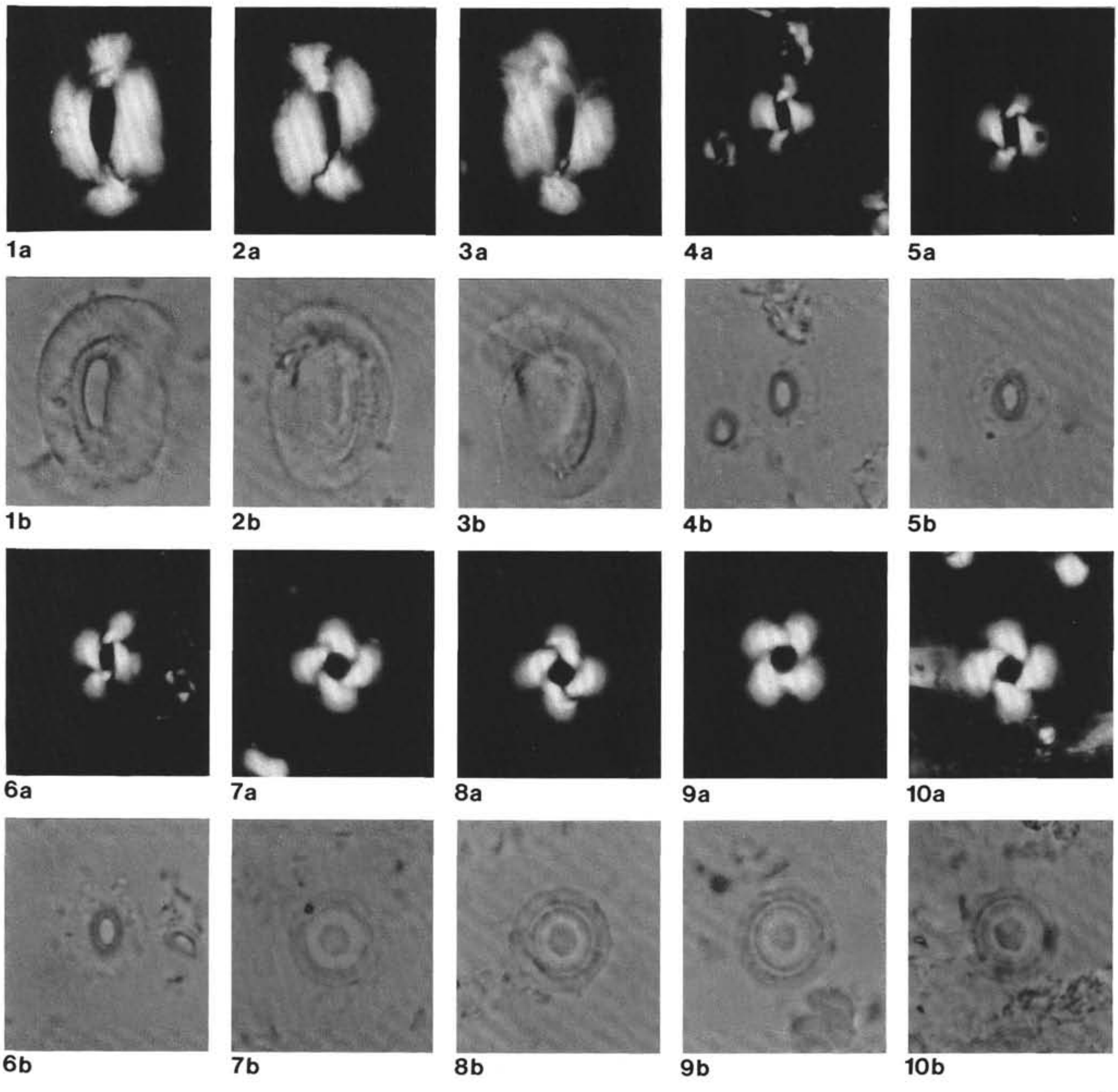

Plate 1. (Scale bar 5 μm) **1–3.** *Helicosphaera omanica*, n. sp., 1. Holotype, TOCCN 16952(1), Sample 117-721A-4H-3, 115–117 cm. 2, 3. Paratype, TOCCN 16952(2), 16952(3), Sample 117-721A-4H-3, 115–117 cm. **4–6.** *Reticulofenestra ampla*, n. sp. 4. Holotype, TOCCN 16954(1), Sample 94-607-13H-CC. 5. Paratype, TOCCN 16953, Sample 94-607-13H-6, 47–48 cm. 6. Paratype, TOCCN 16954(2), Sample 94-607-13H-CC. **7–10.** *Reticulofenestra asanoi* Sato and Takayama. Sample BSUS 16, Umegase Formation, Boso Peninsula, Japan.

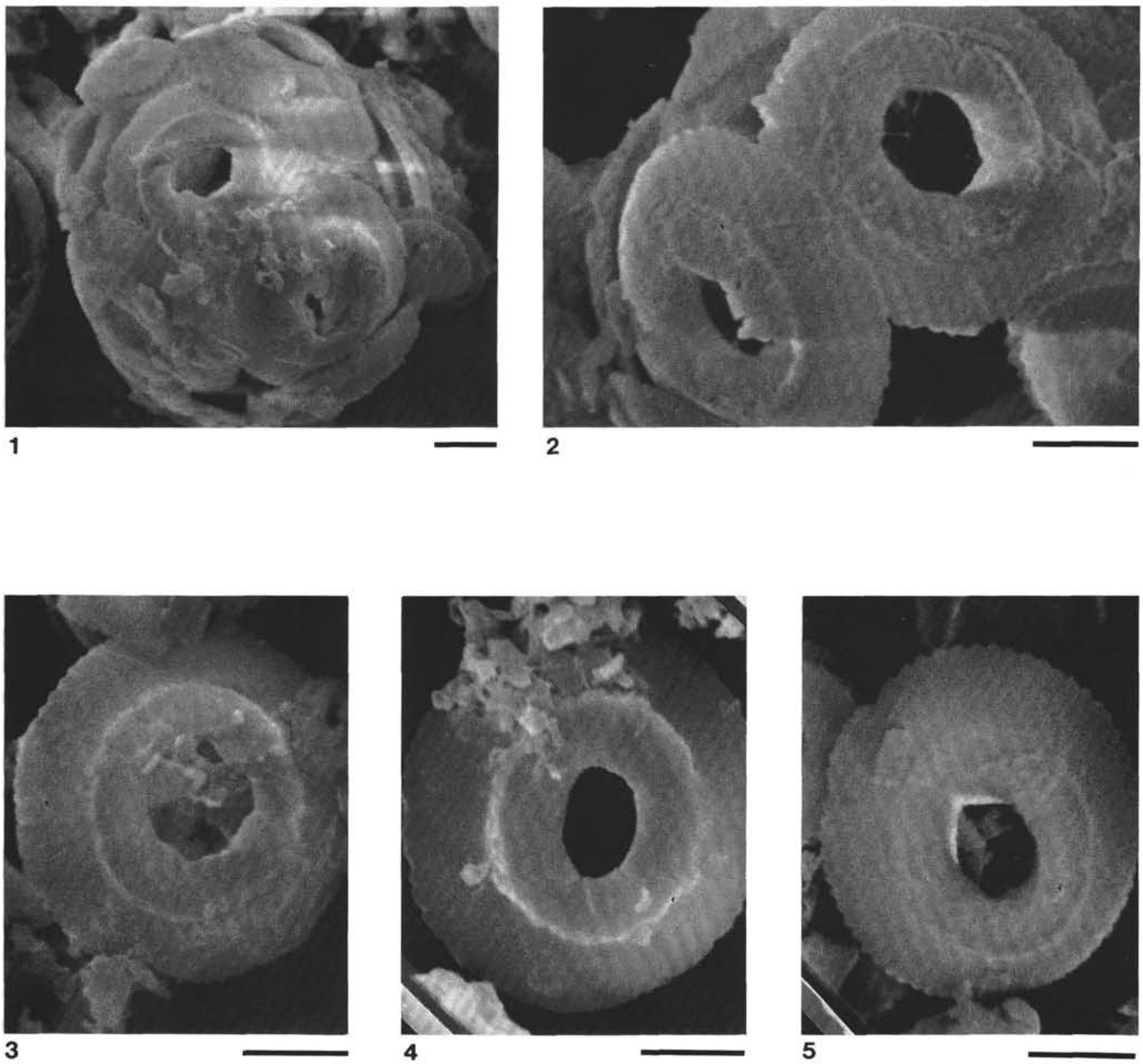

Plate 2. (Scale bar 2 μm) **1–5.** *Reticulofenestra asanoi* Sato and Takayama. Sample 117-722A-4H-4, 115–117 cm.