



# 12. MIDDLE EOCENE - LATE OLIGOCENE BATHYAL BENTHIC FORAMINIFERA (WEDDELL SEA): FAUNAL CHANGES AND IMPLICATIONS FOR OCEAN CIRCULATION

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## ABSTRACT

Lower bathyal benthic foraminiferal faunas from Maud Rise (Weddell Sea, Antarctica) underwent gradual, but stepped extinctions from middle Eocene through Oligocene, with steps at about 46.4-44.6 Ma, 40-37 Ma, and 34-31.5 Ma. Faunal changes at these high latitudes encompassed decreasing diversity and increasing relative abundance of epifaunal species, in combination with loss of large, heavily calcified *Bulimina* species (first step), followed by the disappearance of all *Bulimina* species and the appearance of *Turrilina alsatica* (second step), followed by a strong decrease in abundance of *T. alsatica*, resulting in faunas dominated by *Nuttallides umbonifera* (third step). These faunal changes may reflect the reaction of the fauna to gradual cooling (and thus a gradual increase in corrosiveness) of the high-latitude lower bathyal waters. The gradual nature of the faunal changes in lower bathyal benthic foraminiferal assemblages and the absence of catastrophic extinctions (on Maud Rise, as well as worldwide) suggest that the psychrosphere was established as a result of gradual cooling of surface waters at high latitudes and that lower bathyal waters were formed by cooling and sinking at high latitudes during the middle Eocene through Oligocene.

## INTRODUCTION

Dramatic climate changes occurred in the Cenozoic, especially from middle Eocene through early Oligocene (e.g., Shackleton and Kennett, 1975; Kennett and Shackleton, 1976; Kennett, 1977; Savin, 1977; Shackleton and Boersma, 1981; Mercer, 1983; Shackleton, 1986; Miller et al., 1987a; Kennett and Barker, 1990;

Thomas, 1989, 1990a; Webb, 1990; Barron et al., 1991; Zachos et al., 1991; Wise et al., 1991). Deep waters in the world's oceans and surface waters at high latitudes cooled strongly after the very warm early Eocene: early Eocene surface water temperatures at high latitudes were estimated to have been about 15-17°C (Stott et al., 1990). At some time during the middle Eocene - early Oligocene the psychrosphere was established (Benson, 1975), as well as at least partial ice sheets on eastern Antarctica (Kennett and Shackleton, 1976; Keigwin and Keller, 1984; Miller and Thomas, 1985; Miller et al., 1987a; Kennett and Barker, 1990; Barron et al., 1991; Wise et al., 1991). The extent and nature of these ice sheets (whether they were true continental ice sheets, temperate ice sheets or upland and coastal glaciers) is under considerable discussion, even after the large increase in knowledge resulting from Ocean Drilling Program (ODP) Legs 113, 114, 119, 120 at high southern latitudes (Kennett and Barker, 1990; Barron et al., 1991; Wise et al., 1991).

There is no agreement on the interpretation of the oxygen isotopic records of benthic foraminifers, especially in how far this record demonstrates establishment of continental ice sheets (the ice-volume effect), and in how far it represents cooling of deep waters in the oceans (e.g., Matthews and Poore, 1980; Poore and Matthews, 1984; Keigwin and Corliss, 1986; Miller et al., 1987a; Prentice and Matthews, 1988; Wise et al., 1991; Zachos et al., 1991; Oberhaensli et al., 1991). Therefore it is not clear whether equatorial surface waters were cooler than now during these warm periods (e.g., Shackleton, 1984), or remained essentially at the same temperature throughout the



Cenozoic, as indicated by the distribution of tropical biota such as hermatypic corals, mangroves and larger foraminifera (Adams et al., 1990). There also is no agreement on whether the flat Eocene isotopic gradients in planktonic foraminifera from low to high latitudes in the Atlantic Ocean reflect very low to flat temperature gradients (Shackleton and Boersma, 1981; Shackleton, 1984; Keigwin and Corliss, 1986; Boersma et al., 1987), or are influenced by fresh-water influx at higher latitudes (e.g., Wise et al., 1991). In addition, there is no agreement regarding modes of deep-water formation in the oceans during the Paleogene: did deep oceanic waters (intermediate and bottom water masses) predominantly form at high latitudes after cooling and sinking, as they do today (Manabe and Bryan, 1985; Barrera et al., 1987; Katz and Miller, 1991), or did they predominantly form at low latitudes by evaporation for at least part and possibly all of this period (Chamberlain, 1906; Shackleton and Boersma, 1981; Brass et al., 1982; Hay, 1989)? Was the circulation of the deep and possibly intermediate water masses of the oceans thus essentially reversed (from dominant formation at high, to dominant formation at low latitudes) in all or part of the Paleogene (e.g., Kennett and Stott, 1990)? Did a final reversal from such a halothermal circulation system to the present system cause the origination of the psychrosphere? Oceans "running the reverse" from the modern circulation pattern (i.e., sinking at low latitudes) might be required to model satisfactorily the high heat transfer from low to high latitudes required to maintain the warm Eocene climate at high latitudes (Barron, 1985, 1987). Carbon and oxygen isotopic data and benthic foraminiferal data, however, do not unequivocally point to the existence of such an evaporation-driven deep water circulation, and may be read to indicate an overall Paleocene ocean circulation dominated by deep-water formation at high latitudes, although short (<0.5 m.y.) periods of high-volume formation of warm, salty bottom waters might have occurred (Barrera et al., 1987; Miller et al., 1987b; Thomas, 1989; 1990a; Kennett and Stott, in prep.; Katz and Miller, 1991; Zachos et al., 1991).

Recent deep-water benthic foraminiferal faunas reflect the physicochemical properties

of water masses, and faunal patterns thus reflect global deep oceanic circulation (see e.g., Douglas and Woodruff, 1981, and Culver, 1987, for a review). Many studies of bathyal and upper abyssal benthic foraminifera from the Atlantic and Pacific Oceans have demonstrated that there were no catastrophically sudden extinctions at the end of the Eocene: there were extinctions over a period of several millions of years from the middle Eocene into the early Oligocene in benthic foraminiferal faunas as well as in ostracode faunas (e.g., Corliss, 1981; Tjalsma and Lohmann, 1983; Miller, 1983; Miller et al., 1984; Boersma, 1984; 1985; Corliss and Keigwin, 1986; Berggren and Miller, 1989; Boltovskoy, 1980; Boltovskoy and Boltovskoy, 1988; 1989; reviews in Douglas and Woodruff, 1981; and in Culver, 1987).

Benthic foraminiferal faunas from high latitudes might be expected to be a good source of information on deep-water formational processes: at these high latitudes deep waters are not only cool or cold, but also "young", i.e., these waters were in equilibrium with the atmosphere only a short time before reaching the site, and thus rich in oxygen, poor in nutrients and CO<sub>2</sub> (a short period means short compared to the turnover time of the oceans, around 1000 years; Gascard, 1990). Deep waters formed by evaporation at subtropical latitudes are relatively warm, and they must have travelled from sub-equatorial latitudes to the high latitudes, thus they are "old" (i.e., have not been in contact with the atmosphere for at least several hundreds of years, and are enriched in CO<sub>2</sub> and nutrients, depleted in oxygen). Thomas (1989; 1990a, 1990b) argued that bathyal benthic foraminiferal faunal changes at Sites 689 and 690 on the Maud Rise (Weddell Sea, Antarctica) indicate that bathyal waters at these sites formed at high latitudes during the Maestrichtian and early Paleocene, with at least one, possibly several short (less than 0.5 m.y.) periods of reversal of ocean circulation at the end of the Paleocene and in the earliest Eocene, during which warm salty deep waters bathed the Maud Rise sites (in agreement with conclusions by Katz and Miller, 1991, for faunas from ODP Leg 114 Sites in the southernmost Atlantic Ocean). The period of most intense deep-water formation at low latitudes was said to be at the end of the Paleocene, and the cause of



the worldwide extinction of deep-water benthic foraminifers, the most severe and sudden extinction event of benthic foraminifers in the entire Cenozoic (Schnitker, 1979; Tjalsma and Lohmann, 1983; Miller et al., 1987; Boltovskoy and Boltovskoy, 1988; 1989; Katz and Miller, 1991; Mackensen and Berggren, 1991; Nomura, 1991; Kaiho, 1991).

In this paper I present information on middle Eocene through upper Oligocene lower bathyal benthic foraminiferal faunas from Ocean Drilling Program Site 689 (paleodepth about 1500-2000 m) on Maud Rise (Antarctica), in order to evaluate the response of benthic foraminiferal faunas to changing climate and deep-water circulation.

## MATERIALS AND METHODS

Ocean Drilling Program Sites 689 (64°31.009' S, 03°05.996' E, present water depth 2080 m) and 690 (65°9.629' S, 1°12.296' E, present water depth 2914 m) were drilled on Maud Rise, an aseismic ridge on the eastern entrance of the Weddell Sea (Barker, Kennett et al., 1988; Figure 12.1). Site 689 is on the northeastern side of Maud Rise, Site 690 is 116 km to the southwest, on the southwestern flank. The sediments are lowermost Maestrichtian through Pleistocene biogenic oozes (Figure 12.2; see also Thomas et al., 1990). Core recovery was good and deformation minimal over most of the drilled section (Barker, Kennett et al., 1988). The Upper Cretaceous through lower middle Eocene consists of chalks and calcareous oozes. Upper middle Eocene through lowermost Miocene are mixed siliceous-calcareous biogenic oozes, with a gradual increase in the siliceous component up-section. Middle Miocene and younger sediments are dominantly siliceous oozes. Calcium carbonate microfossils shows signs of dissolution from the uppermost middle Eocene upwards (Barker, Kennett et al., 1988; Diester-Haass, 1991).

Sites 689 and 690 are on an aseismic ridge, so that backtracking following Parsons and Sclater's (1977) methods for sites on normal oceanic crust is not justified. Backtracking methods may be valid even for sites on oceanic plateaus, however, although the original depth of the site cannot be assumed to have been at the depth of average ridge-crest (Detrick et al., 1977; Coffin, 1991). Backtrack-

ing of Site 689 resulted in an estimate of 1300-1700 m paleodepth for the middle Eocene-Oligocene, using data on sediment density after Barker, Kennett et al. (1988), and the correction for sediment loading after Crough (1983). This paleodepth agrees with the depth estimates of 1000-1500 m from benthic foraminiferal data (Thomas, 1990a).

Biostratigraphic records of calcareous nannofossils and planktonic foraminifers combined with magnetostratigraphy show that there are several unconformities at both sites (Figure 12.2). At Site 690 large parts of the upper and uppermost middle Eocene are not represented in the sediments (Thomas et al., 1990). At both sites there are unconformities across the Oligocene/Miocene boundary, at Site 689 corresponding to the lower part of paleomagnetic Chronozone C6 and the upper part of C7 (20.45-25.60 Ma). Another unconformity at Site 689 covers most of the lower Eocene and parts of the lowermost middle Eocene (lower Chronozone C21 through upper Chronozone C24, about 51-56 Ma). The section appears to be complete (within the stratigraphic resolution) between these two unconformities, i.e., an interval corresponding to the time between roughly 51 and 27 Ma (lower middle Eocene through lower upper Oligocene). All data are presented versus sub-bottom depth (with nannofossil zonation after Pospichal and Wise, 1990; Wei and Wise, 1990). Data were not plotted versus numerical age because of the possible revisions of the age of the Eocene/Oligocene boundary (Berggren et al., this volume); numerical ages follow Berggren et al. (1985). All numerical ages were derived by extrapolation between paleomagnetic tie points listed in Thomas et al. (1990).

Data are presented from 93 samples between 68.92 and 202.41 mbsf (26.80 - 50.99 Ma, see Thomas et al., 1990), i.e., from the middle Eocene through Oligocene section at Site 689. Preliminary data on the faunas were published by Thomas (1989; 1990a), but data over the middle Eocene-Oligocene in these papers were limited to a sample resolution of 2 samples per core (9.6 m). Sample resolution for this paper was 1.5 m, resulting in an average time-resolution of between 0.25 and 0.30 m.y.

Samples (15 cm<sup>3</sup>) were dried at 75°C, soaked in Calgon, and washed over a sieve with openings of 63 µm; residues were dried at 75°C.



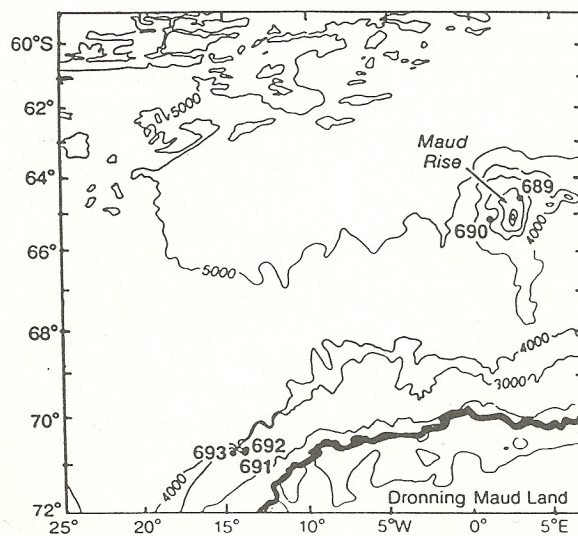
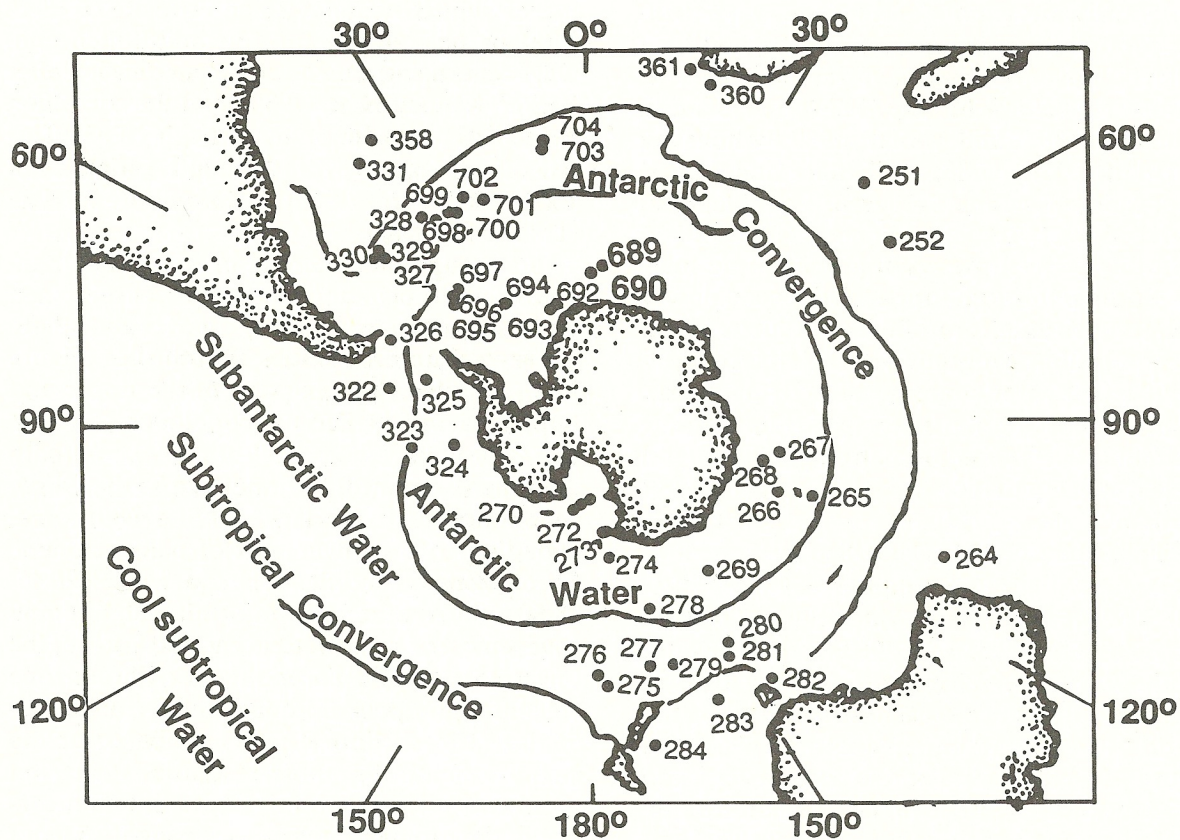


FIGURE 12.1. Location of Sites 689 and 690 on Maud Rise.



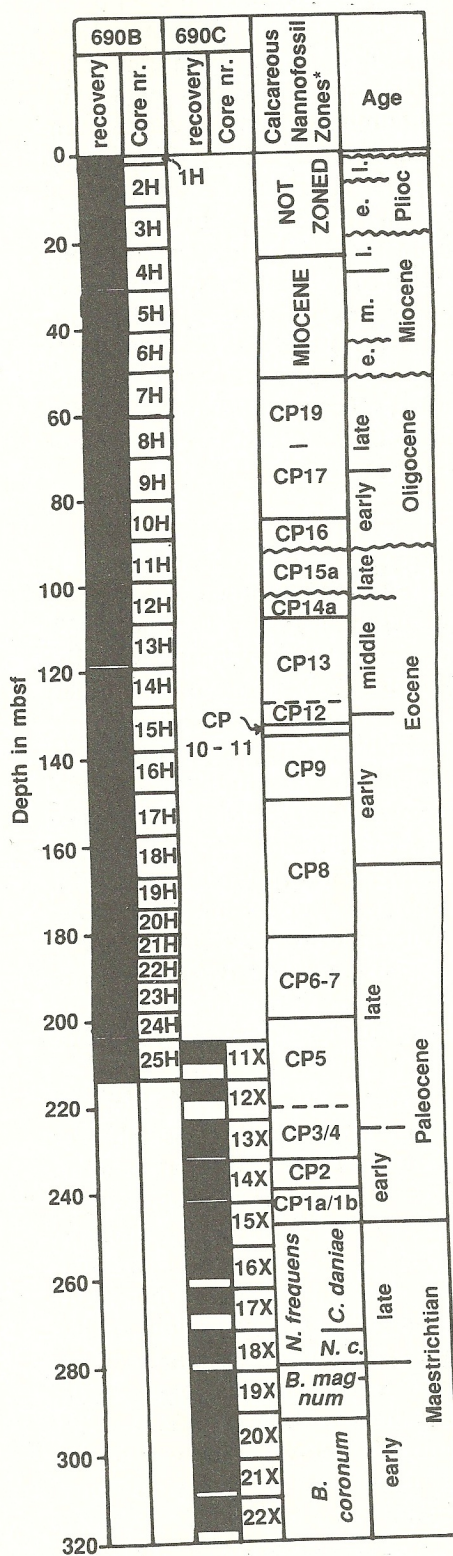
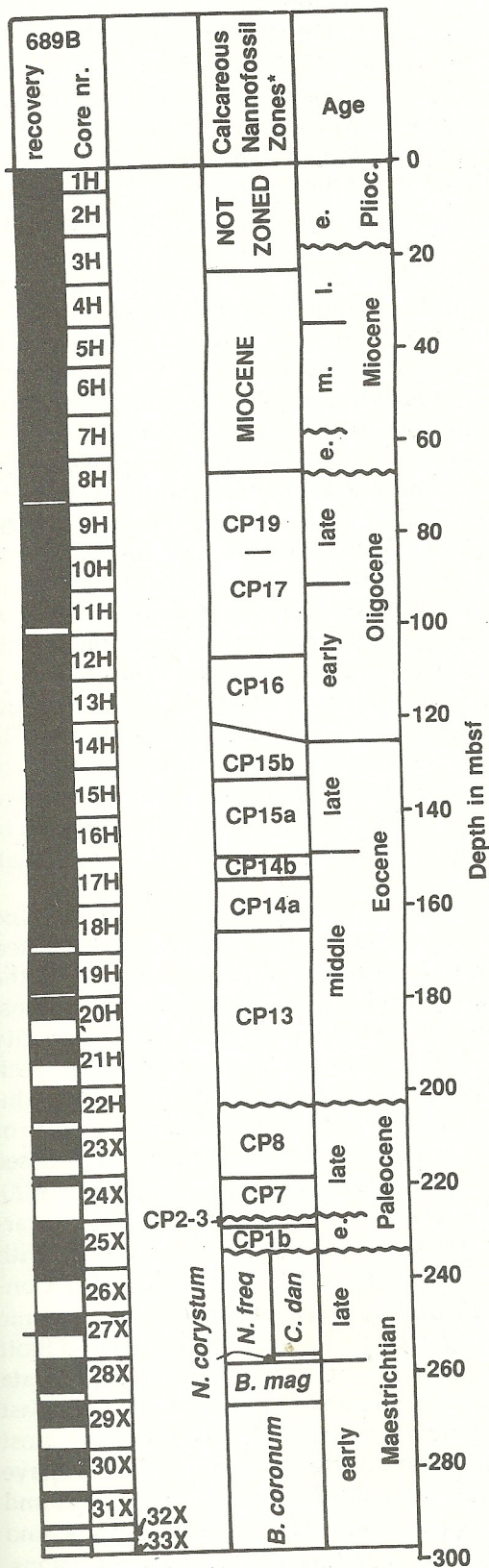


FIGURE 12.2. Core recovery and stratigraphy at Maud Rise, Sites 689 (left) and 690 (right). Calcareous nannofossil zones after Pospichal and Wise (1990) and Wei and Wise (1990).



Specimens were studied from the greater than 63  $\mu\text{m}$  size fraction in order to ensure representation of smaller species (Thomas, 1985; Schroeder et al., 1987). At the beginning of the study rarefaction curves were drawn for several samples (plots of numbers of species versus number of specimens; Thomas, 1985). Rarefaction curves become parallel to the specimen axis at about 270 specimens, thus 300 specimens or more were picked from the sample or a split of the sample. There is no correlation between number of specimens and number of species for the studied samples, demonstrating that the number of species counted per sample does not reflect the number of counted specimens. Taxonomy is discussed in Thomas (1990a), and largely follows van Morkhoven et al. (1986).

## RESULTS

Cretaceous through Neogene benthic foraminiferal faunas at Sites 689 and 690 were subdivided into eight assemblages by Thomas (1989; 1990a), using first and last appearances as discussed below (Figure 12.3). The interval studied in this paper contains Thomas' benthic foraminiferal assemblage 2 (upper boundary in the Miocene, lower boundary in the uppermost Eocene, Chronozone C16N, 38.5Ma), assemblage 3 (uppermost Eocene, 38.5Ma, through upper middle Eocene, lower part of Chronozone C20N, 46Ma) and assemblage 4 (upper middle Eocene, 46Ma through middle lower Eocene, 54.5 Ma). The latter was subdivided into two sub-assemblages, 4A and 4B, with a boundary close to the middle/lower Eocene boundary (Chronozone C21/C22 boundary) at about 52Ma.

Within the time-resolution available, the boundaries between the Maud Rise assemblages are largely coeval with the abyssal benthic foraminiferal zonal boundaries proposed by Berggren and Miller (1989), although most of their zonal marker species were not present, very rare, or had different ranges at the Maud Rise sites (Figure 12.3). One exception to this agreement might be that assemblage 2B at Maud Rise appears to agree better with bathyal zone BB5 than with abyssal zone AB8 (as discussed further below), whereas lower bathyal faunas usually show larger resemblance to abyssal than to middle bathyal assemblages. Another exception to the agreement between the Maud Rise benthic

foraminiferal assemblages and the zones in Berggren and Miller (1989) might be the assemblage boundary (2/3) estimated to occur at 38.5Ma at Site 689, i.e., earlier than the boundary between Zones AB7 and AB8 in Berggren and Miller (1989), which was placed at the Eocene/Oligocene boundary. At Maud Rise this assemblage boundary occurs between 130.31 and 131.81 mbsf (Thomas, 1990a; but see below for discussion), and thus occurred before the globally recognized rapid increase in  $\delta^{18}\text{O}$  values in benthic foraminifera in the lowermost Oligocene (paleomagnetic Chronozone C13R), which at Site 689 is recorded at about 120 mbsf (Thomas et al., 1990; and see below). The benthic faunal boundary occurs below the LAD of the planktonic foraminifer *Globigerina* *index*, which occurs between 128.82 and 129.92 mbsf at Site 689; this LAD was estimated to have occurred at about 38.4Ma in Chronozone C16N (Stott and Kennett, 1990). A different interpretation of the paleomagnetic record is possible (Spiess, 1990), however, which would place this LAD close to the Eocene/Oligocene boundary (Berggren, 1991). In this paper I followed the interpretation of Stott and Kennett (1990), which is in agreement with the interpretation of nannofossil events in Wei and Wise (1990) as shown in Thomas et al. (1990).

All counts are presented in the appendix. Ranges of the more common species are listed (Figure 12.4), and relative abundances of the stratigraphically and paleoecologically most useful taxa provided (Figure 12.5). Diversity (expressed as number of species per 300 specimens), and relative abundance of epifaunal, infaunal and cylindrical taxa (subdivision of taxa in groups according to Thomas, 1990a; see Table 12.1, following Corliss and Chen, 1988), as well as the number of first and last appearances are shown in Figure 12.6, together with the  $\text{CaCO}_3$  content of the sediments (O'Connell, 1990), the oxygen and carbon isotopic values of *Cibicides* spp. of Kennett and Stott (1990), and the bulk carbonate isotopic data from Shackleton and Hall (1990). First and last appearances are strictly local events; for most benthic foraminiferal taxa datum levels have not been globally determined. Thus first and last appearances may be originations and extinctions, or immigrations and emigrations,



Age, Ma	EPOCHS	Thomas, 1990	Berggren & Miller, 1989	
		Assemblages Maud Rise	AB zones	BB zones
0	Pliocene	1	AB12	BB14
5				BB13
10				BB12
10	late M	barren	AB11	BB11
15	middle o			BB10
15	middle c			BB9
20	early e	2A	AB10	BB8
25	late			BB7
30	early Oligo-			BB6
35	late cene	2B	AB9	BB5
40	early			BB4
45	late			BB3
50	middle E	3	AB8	BB2
55	early c	4A	AB7	
60	late	4B	AB6	
65	early	5	AB5	BB1
70	late Paleocene	6	AB4	BB1
75	early Maestr.	7	AB3	
		8	AB2	

FIGURE 12.3. Benthic foraminiferal assemblages as recognized on Maud Rise at Sites 689 and 690, after Thomas (1990a). The assemblages are compared with the benthic foraminiferal zones for the bathyal regions (BB zones) and abyssal regions (AB zones) as defined by Berggren and Miller (1989).



FIGURE 12.4. Ranges of most common species at Site 689, versus sub-bottom depth, arranged by highest appearance.

appearance:

very rare	( 0 - 4 %)
rare	( 5 - 9 %)
few	(10-24 %)
common	(25-49 %)
abundant	( > 50 %)

Species Location Index: index numbers are the columns in which species appear:

1	<i>Anomalina spissiformis</i>	33	<i>Gyroidinoides mediceus</i>
2	<i>Anomalinoides pseudogrosserugosa</i>	40	<i>Gyroidinoides planulatus</i>
35	<i>Anomalinoides semicribrata</i>	11	<i>Gyroidinoides soldanii</i>
3	<i>Astrononion pusillum</i>	12	<i>Lenticulina</i> spp.
4	<i>Astrononion umbilicatum</i>	36	<i>Nonion havanense</i>
34	<i>Bigenenerina nodosaria</i>	45	<i>Nuttallides truempyi</i>
5	<i>Bolivina decussata</i>	13	<i>Nuttallides umbonifera</i>
38	<i>Bolivina huneri</i>	14	<i>Oridorsalis tener</i>
48	<i>Bulimina callahani</i>	15	<i>Oridorsalis umbonatus</i>
37	<i>Bulimina elongata</i>	16	<i>Pleurostomella</i> spp.
46	<i>Bulimina ovula</i>	17	<i>Pullenia bulloides</i>
49	<i>Bulimina semicostata</i>	18	<i>Pullenia quinqueloba</i>
43	<i>Bulimina simplex</i>	19	<i>Pullenia salisburyi</i>
6	<i>Cibicidoides mundulus</i>	20	<i>Reussella tortuosa</i>
42	<i>Cibicidoides praemundulus</i>	47	<i>Siphogenerinoides eleganta</i>
44	<i>Cibicidoides trincherasensis</i>	21	<i>Stilostomella aculeata</i>
7	<i>Eggerella bradyi</i>	22	<i>Stilostomella annulifera</i>
8	<i>Eilohedra weddellensis</i>	32	<i>Stilostomella consobrina</i>
9	<i>Epistominella exigua</i>	23	<i>Stilostomella subspinosa</i>
39	<i>Fursenkoina bradyi</i>	24	<i>Turrilina alsatica</i>
41	<i>Fursenkoina fusiformis</i>	25	unilocular species
29	<i>Globocassidulina subglobosa</i>	26	uniserial lagenids
30	<i>Gyroidinoides acutus</i>	27	<i>Uvigerina graciliformis</i>
31	<i>Gyroidinoides girardanus</i>	28	<i>Uvigerina peregrina</i> group
10	<i>Gyroidinoides lamarckianus</i>		

the latter geographically as well as depth-wise (vertical).

#### Assemblage 4 (lower to middle middle Eocene)

The assemblage occurs at Site 689 from Sample 689B-22X-4, 40-42cm (202.41m; just above an unconformity between calcareous nannofossil zones CP8 and CP12). Assemblage 4 is characterized by a high diversity (36 to 58 species per 300 specimens, average  $44.5 \pm 5.6$  species). Characteristic species are *Bulimina semicostata*, *Bulimina trinitatensis*, and *Bulimina callahani*, all large, ornamented, heavily calcified buliminid species; *Bulimina simplex*, a small, smooth-walled buliminid species; and

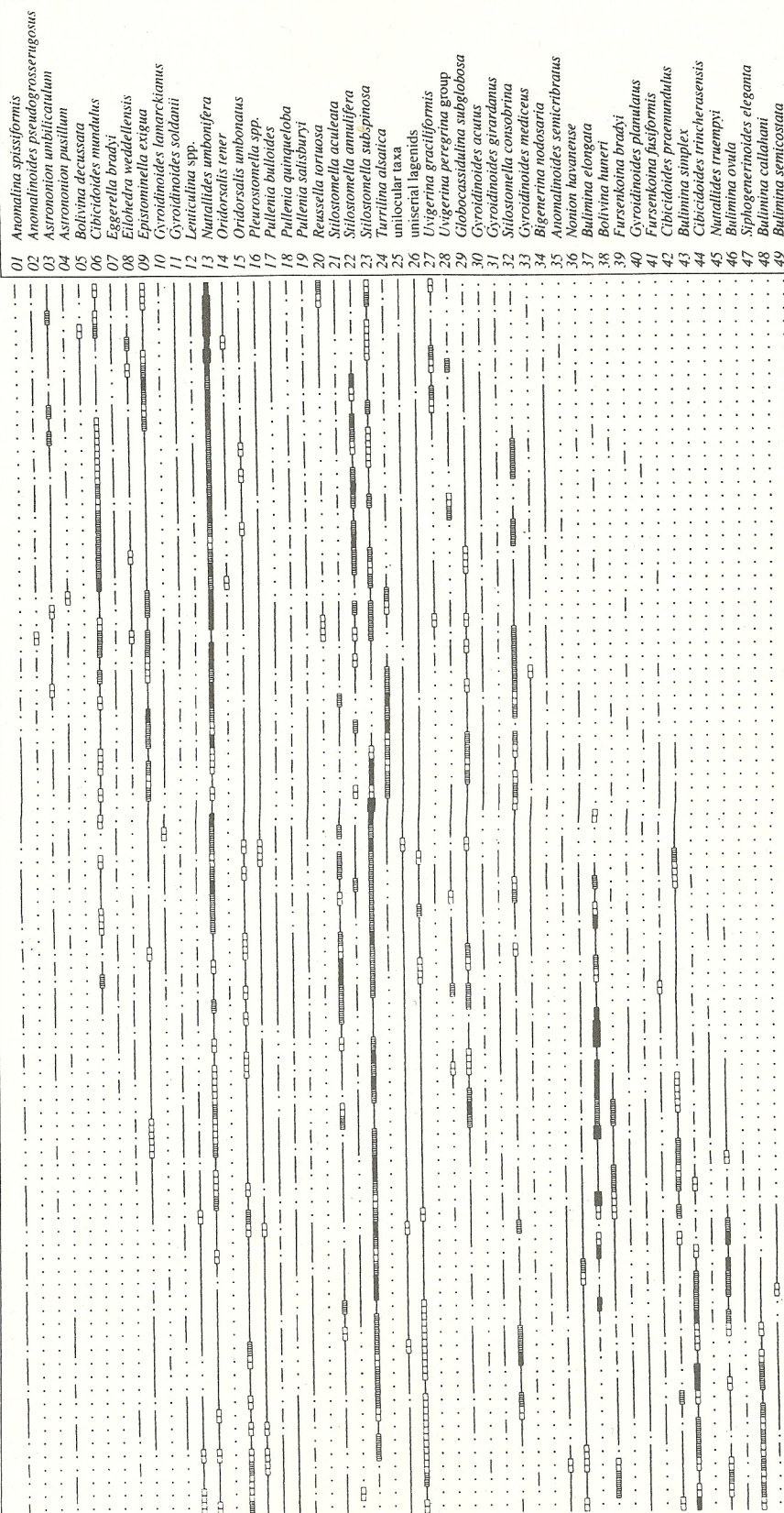
*Siphogenerinoides eleganta*. Uniserial lagenid species and lenticulinids are common and diverse. *Stilostomella* spp., especially *S. subspinosa*, are common in many samples (Figures 12.4, 12.5, 12.6). Other commonly present species are *Oridorsalis umbonatus*, and *Gyroidinoides* spp.; *Cibicidoides praemundulus* is usually present and common to rare, as is *Nuttallides umbonifera*. The relative abundance of *Nuttallides truempyi* fluctuates strongly (Figure 12.5), but the species is most common in the upper part of the assemblage.

The lower boundary of the assemblage was taken at the first appearance (FA) of *Siphogenerinoides eleganta*, but its age could not be



SAMPLE DEPTH.  
MBSF

08H-5, 040-043cm 068.92  
08H-6, 041-043cm 070.42  
08H, CC 071.93  
09H-1, 040-042cm 072.51  
09H-2, 040-042cm 074.01  
09H-3, 040-042cm 075.51  
09H-4, 040-042cm 077.01  
09H-5, 040-042cm 078.51  
09H-6, 040-042cm 080.01  
09H, CC 080.66  
10H-1, 039-043cm 082.11  
10H-2, 039-043cm 083.61  
10H-3, 039-043cm 085.11  
10H-4, 039-043cm 086.61  
10H-5, 039-043cm 088.11  
10H-6, 039-043cm 089.61  
10H, CC 090.49  
11H-1, 040-044cm 091.72  
11H-2, 040-044cm 093.22  
11H-3, 040-044cm 094.72  
11H-4, 040-044cm 096.22  
11H-5, 040-044cm 097.72  
11H, CC 098.96  
12H-1, 040-042cm 101.41  
12H-2, 040-042cm 102.91  
12H-3, 040-042cm 104.41  
12H-4, 040-042cm 105.91  
12H-5, 040-042cm 107.41  
12H-6, 040-042cm 108.91  
12H, CC 110.60  
13H-1, 040-042cm 111.01  
13H-2, 040-042cm 112.51  
13H-3, 040-043cm 114.01  
13H-4, 040-042cm 115.51  
13H-5, 040-042cm 117.01  
13H-6, 040-042cm 118.51  
13H, CC 120.20  
14H-1, 043-045cm 120.64  
14H-2, 041-043cm 122.12  
14H-3, 041-043cm 123.62  
14H-4, 041-043cm 125.12  
14H-5, 041-043cm 126.62  
14H-6, 041-043cm 128.12  
14H, CC 129.76  
15H-1, 040-043cm 130.32  
15H-2, 040-043cm 131.82  
15H-3, 040-043cm 133.32  
15H-4, 040-043cm 134.82  
15H-5, 040-043cm 136.32  
15H-6, 040-043cm 137.82  
15H, CC 139.40  
16H-1, 040-042cm 139.81  
16H-2, 040-042cm 141.31  
16H-3, 040-042cm 142.81  
16H-4, 040-042cm 144.31  
16H-5, 040-042cm 145.81  
16H-6, 040-042cm 147.31  
16H-7, 040-042cm 148.81  
16H, CC 149.09  
17H-1, 040-042cm 149.51  
17H-2, 040-042cm 151.01  
17H-3, 040-042cm 152.51  
17H-4, 040-042cm 154.01  
17H-5, 040-042cm 155.51  
17H-6, 040-042cm 157.01  
17H-7, 040-042cm 158.51  
17H, CC 158.80  
18H-1, 039-041cm 159.20  
18H-2, 039-041cm 160.70  
18H-3, 039-041cm 162.20  
18H-4, 039-041cm 163.70  
18H-5, 039-041cm 165.20  
18H, CC 166.85  
19H-1, 039-042cm 167.31  
19H-2, 039-042cm 168.81  
19H-3, 039-042cm 170.31  
19H-4, 039-042cm 171.81  
19H-5, 039-042cm 173.31  
19H-6, 039-042cm 174.81  
19H, CC 177.05  
20H-1, 040-044cm 178.52  
20H-2, 040-044cm 180.02  
20H-3, 040-044cm 181.52  
20H-4, 040-044cm 183.02  
20H, CC 184.46  
21H-1, 040-044cm 188.22  
21H-2, 040-044cm 189.72  
21H-3, 040-044cm 191.22  
21H, CC 192.28  
22X-1, 040-042cm 197.91  
22X-2, 040-042cm 199.41  
22X-3, 040-042cm 200.91  
22X-4, 040-042cm 202.41





ascertained unequivocally because of stratigraphic problems at Site 689 as well as at Site 690. Thomas (1990a) stated that the upper boundary of the assemblage occurred between samples 689B-19H-2, 40-42 cm (168.68 mbsf, 45.55 Ma) and 689B-19H-1, 40-42 cm (167.31 mbsf, 45.14 Ma); at Site 690 the upper boundary occurred at an unconformity. At Site 689 this upper boundary is difficult to locate precisely, however, because the changes in the benthic foraminiferal faunas occur gradually, from Sample 689B-19H-5, 39-41 cm (173.31 mbsf; 46.64 Ma) through Sample 689B-18H-5, 39-41 mbsf (165.20 mbsf; 44.57 Ma; Figures 12.4, 12.5; Appendix). These gradual changes include the last appearances of *S. eleganta* and all large, heavily calcified buliminids, the last appearance of *B. simplex*, the last common appearance of *N. truempyi*, and a decrease in diversity, largely as the result of a loss of diversity of uniserial lagenids and lenticulinids. The first common occurrence of *Bulimina elongata*, a buliminid species that is typical of the next younger assemblage, is within the interval of assemblage 4, in sample 689B-19H-5, 39-41 cm.

#### Assemblage 3 (middle Eocene - upper Eocene)

The assemblage occurs at Site 689 above the interval of gradual change at the upper part of assemblage 4 (173.31-165.20 mbsf; 46.64-44.57 mbsf). The assemblage is characterized by a lower diversity than the older assemblage 4 (30 to 49 species, average  $40.9 \pm 5.1$  species). Typically common to abundant species are *Bulimina elongata*, a small, smooth-walled buliminid, with strongly fluctuating relative abundance (Figure 12.5), *Nuttallides umbonifera* (above sample 689B-15H-5, 40-42 cm; 136.32 mbsf, 39.58 Ma), *Globocassidulina subglobosa*, *Stilostomella* spp., *Bolivina huneri* (below sample 689B-17H-1, 40-42 cm, 149.51 mbsf, 40.88 Ma), and both *Cibicidoides praemundulus* and *Cibicidoides mundulus* over most of the assemblage interval.

Thomas (1990a) located the upper boundary of assemblage 3 between samples 689B-15H-2, 40-42 cm (131.82 mbsf; 38.80 Ma) and 689B-15H-1, 40-42 cm (130.31 mbsf, 38.50 Ma). The assemblage boundary is difficult to determine precisely because of the gradual nature of faunal change. The upper boundary was chosen at the first appearance of *Turrilina alsatica* and the

last common appearance of *Bulimina elongata*. The former species, however, occurs sporadically from sample 689B-16H-1, 40-42 cm (139.81 mbsf, 39.93 Ma) up, with a first common appearance in Sample 689B-14H-3, 41-43 cm (123.62 mbsf, 37.09 Ma). The latter species fluctuates strongly in relative abundance, with its last common continuous appearance in sample 689B-15H-2, 40-43 cm (131.82 mbsf, 38.80 Ma), but another common appearance (above several samples without specimens) in sample 689B-14H-4, 41-43 cm (125.12 mbsf, 37.69 Ma). Thus there is an interval of gradual changes in the benthic foraminiferal faunas, from 139.81 mbsf (39.93 Ma) through 123.62 mbsf (37.09 Ma). This gradual faunal change encompasses a decrease in relative abundance of infaunal species (largely represented by *B. elongata*, Figure 12.6), and an increase in epifaunal and cylindrical taxa.

#### Assemblage 2 (upper Eocene - lower Miocene)

Assemblage 2 occurs above the interval of gradual faunal change through the top of the interval studied for this paper. The assemblage is characterized by much lower diversity than the older assemblages (22 through 46 species per 300 specimens, average  $32.9 \pm 6.5$  species). Thomas (1989, 1990a) did not subdivide the assemblage, although she noticed that *T. alsatica* is common in the lower part of the assemblage at Sites 689 and 690. In this study, I propose a subdivision in a lower sub-assemblage 2B (characterized by the common to abundant occurrence of *T. alsatica*), and an upper sub-assemblage 2A (*T. alsatica* rare or absent). The boundary between these sub-assemblages cannot be located precisely (Figures 12.4, 12.5): the last common continuous occurrence of the species is in sample 689B-12H, CC (110.60 mbsf, 33.80 Ma), but after a few samples without the species the last common occurrence is in sample 689B-12H-1, 40-42 cm (101.41 mbsf; 31.54 Ma).

A strong (although fluctuating) decrease in diversity occurs in sub-assemblage 2B, between the lowest sample in the assemblage (15H-1, 40-43 cm, 130.32 mbsf, 38.5 Ma) and sample 689B-14H-1, 43-45 cm, 120.64 mbsf, 36.16 Ma). This decrease in diversity starts below the strong, sudden increase in  $\delta^{18}\text{O}$ -values in *Cibicidoides* spp. and bulk carbonate (Figure 12.6),



689 B	Core nr.	Calcareous Nannofossil Zones*	Age	Oligocene					Eocene									
				late			early		late			middle						
				CP19	—	CP17	CP16		CP15b	CP15a		CP14b	CP14a	CP13				
				9H	10H	11H	12H	13H	14H	15H	16H	17H	18H	19H	20H	21H	22H	

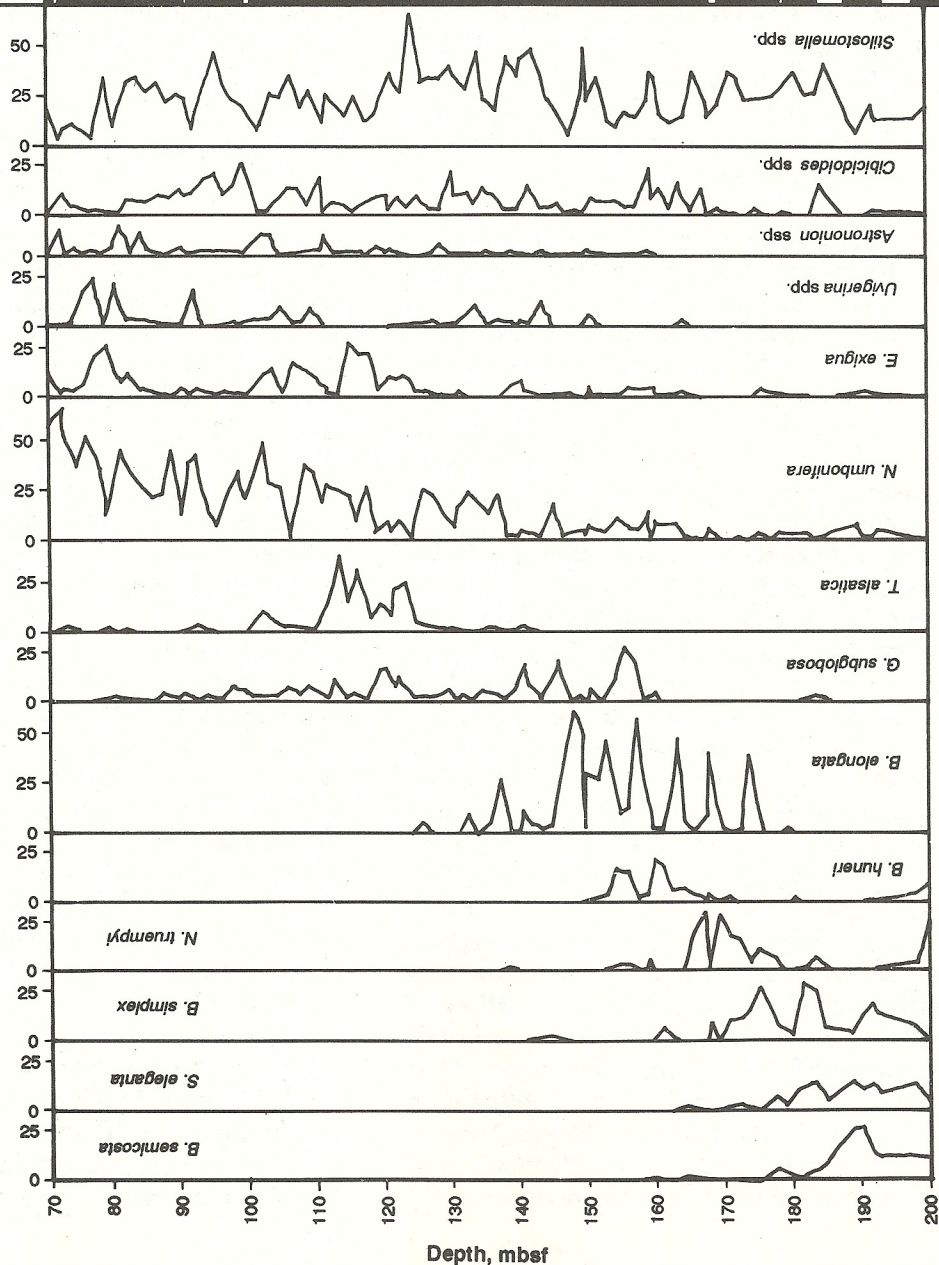


FIGURE 12.5. Relative abundances of the most common species at Site 689, plotted versus sub-bottom depth. Stratigraphy after Wei and Wise (1990).



which occurs between 118.45 mbsf (35.6 Ma) and 121.30 mbsf (36.5 Ma; Kennett and Stott, 1990).

Sub-assemblage 2B is characterized by the common presence of *T. alsatica*, common *Nuttallides umbonifera* and *Stilostomella* spp., common to rare *Epistominella exigua*, *C. mundulus*, and *G. subglobosa*. Sub-assemblage 2A lacks *T. alsatica*, but otherwise resembles sub-assemblage 2B. In sub-assemblage 2A there are a few intervals where the possibly infaunal taxa *Uvigerina* spp. and *Astrononion pusillum* are common (Figure 12.5). Of the *Stilostomella* species, *S. annulifera* is common to abundant especially in sub-assemblage 2B. Within assemblage 2 the diversity decreases upwards, while the relative abundance of epifaunal species (mainly *N. umbonifera*, which reaches up to 70% of the total fauna in the upper part of assemblage 2) increases and that of infaunal species (largely *T. alsatica*) decreases.

#### SPECIES RANGES AND FAUNAL EVENTS

In the middle Eocene through late Oligocene, major changes occurred in the bathyal benthic foraminiferal faunas of Maud Rise (Antarctica). In the first place, the diversity decreased from an average of 45 to an average of 30 species, i.e., a species loss of about 33%, largely as a result of the local disappearance of uniserial lagenids and lenticulid species. In the second place, large, ornamented and heavily calcified buliminid species disappeared during the later part of the middle Eocene, followed by the last disappearance of smaller buliminid species in the late middle to early late Eocene. In the third place, trochospiral (possibly epifaunal) taxa such as *N. umbonifera* and *E. exigua* increased in relative abundance. Thus a middle Eocene, diverse, buliminid (possibly infaunal species)-rich fauna was gradually replaced by a much less diverse fauna dominated by trochospiral (possibly epifaunal) taxa.

Cumulative plots of first and last appearances (Figure 12.6; FAs and LAs; local, not necessarily global events) show alternation of stable intervals and intervals with many last appearances. Such intervals with many last appearances occur between 130 and 140 mbsf (in the transition interval of assemblages 2 and 3, 37-40 Ma), and between 160 and 170 mbsf (43-46 Ma; in and just above the transition interval be-

tween assemblages 3 and 4, 44.5-46.6 Ma). Another interval with an increased number of last appearances occurs between 100 and 105 mbsf, in the transition interval of sub-assemblages 2A and 2B (31-33 Ma). The large number of last appearances above 80 mbsf is not an artifact of end-of-studied-section: these last appearances occur even when data for the higher part of the section are considered (Thomas, 1990a), and result from strong dissolution in the higher part of the section (see also CaCO<sub>3</sub>-values in Figure 12.6; Diester-Haass, 1991).

First appearances are concentrated in the lower part of the section because of the presence of an unconformity at 203 mbsf. An interval with relatively many first appearances occurs roughly between 150 and 160 mbsf (41-43 Ma), another around 140 mbsf (about 40 Ma). The uppermost Eocene and the Oligocene are characterized by very few first appearances (Figure 12.6).

Many authors have described similar faunal patterns for the Eocene: a loss of buliminid species (e.g., Miller, 1983; Site 549 in Bay of Biscay; Douglas and Woodruff, 1981, Pacific; Boersma, 1986, Atlantic Ocean; Boltovskoy and Boltovskoy, 1989, Walvis Ridge, Southern Atlantic; Mueller-Merz and Oberhaensli, 1991, Walvis Ridge, Southern Atlantic), replacement of *N. truempyi* by *N. umbonifera*, and increase in relative abundance of *N. umbonifera*. Boersma (1981) described that *N. umbonifera* increased its depth-range after the earliest Oligocene.

Many specific FAs and LAs, however, occurred at different times at the Maud Rise sites than recorded elsewhere. The last common appearance of *N. truempyi* is commonly recorded elsewhere (e.g., Miller, 1983) near the middle/upper Eocene boundary, but occurs within the middle Eocene (close to the nannofossil zonal boundary between CP13 and CP14a) at Site 689. The LA of *B. semicostata* occurs in the lowermost Oligocene according to van Morkhoven et al. (1986), but in the middle Eocene at the Maud Rise sites.

These two taxa are easily recognized, and the differences in timing are not the result of taxonomic confusion. Differences in opinion on the timing of the FA of *Nuttallides umbonifera* may, however, be an artifact of study methods. This FA is commonly recorded in the lowermost



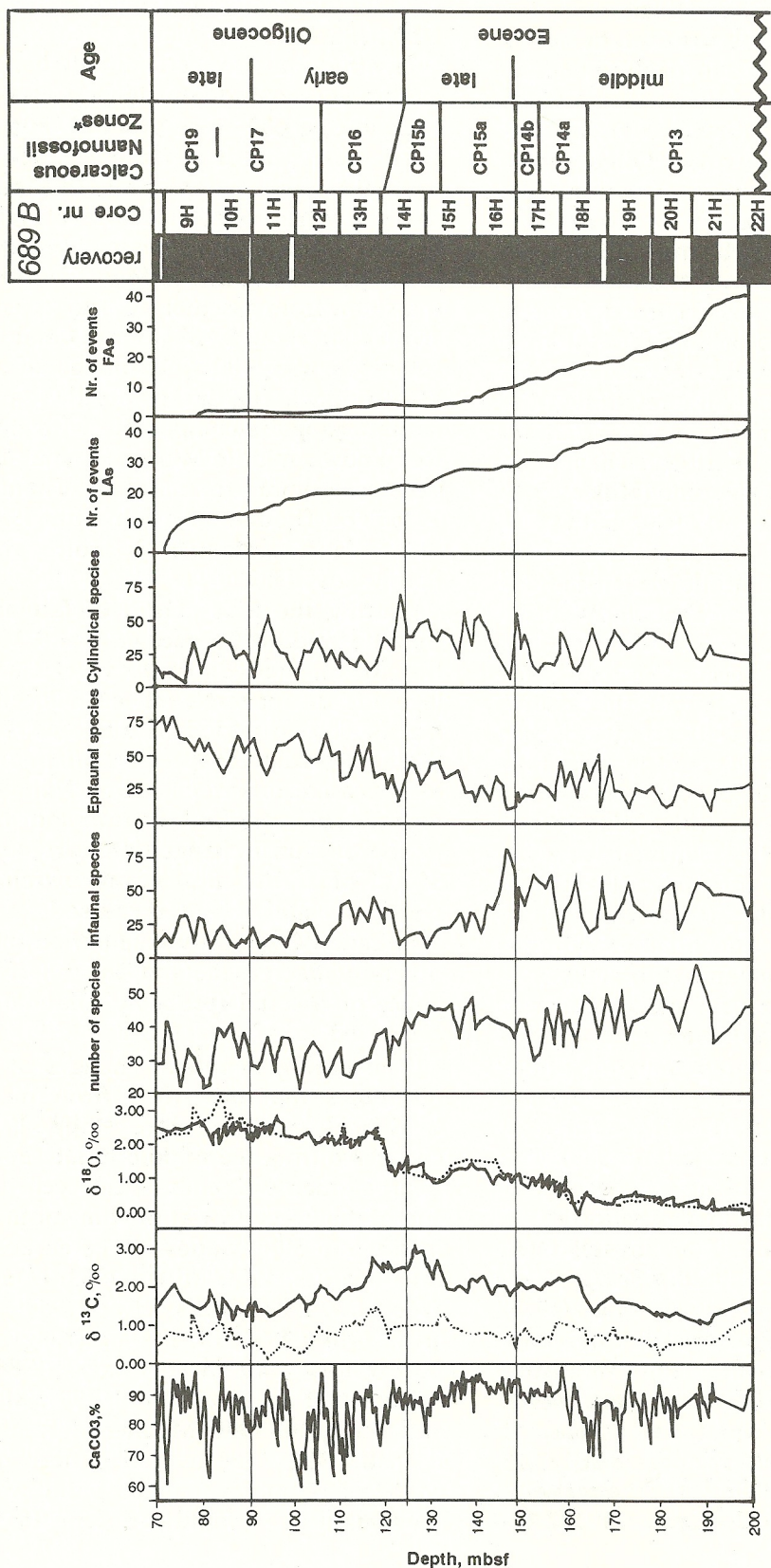


FIGURE 12.6.  $\text{CaCO}_3$  contents of the sediments after O'Connell (1990), carbon and oxygen isotopic data after Kennett and Stott (1990) for *Cibicides* spp. (dotted line), and for bulk sediment after Shackleton and Hall (1990; heavy line), combined with diversity expressed as number of benthic foraminiferal species, relative abundance of infaunal, epifaunal and cylindrical morpho-groups (see Table 12.1), and cumulative plots of first and last appearances. Stratigraphy after Wei and Wise (1990).



Oligocene/uppermost Eocene (Corliss, 1981; Tjalsma and Lohmann, 1983; Miller, 1983), but in the Maud Rise sites it occurs from the lower Eocene. This may be a result of difference in size fractions studied by different authors: the species is small when it first occurs, and becomes larger in the lowermost Oligocene (a common trend in benthic foraminifera; Boltovskoy, 1988). The earliest occurrences of the species can thus easily be missed when the larger than 125 or 150  $\mu\text{m}$  fraction is studied. *Nuttallides umbonifera* was recorded from at least the middle Eocene on in South Atlantic sites (Walvis Ridge; Mueller-Merz and Oberhaensli, 1991), where the authors studied the size fraction larger than 100  $\mu\text{m}$ . *Nuttallides umbonifera* is commonly described as having an acme in the lowermost Oligocene (Miller, 1983; Corliss, 1981; Kaminski et al., 1989), but at Site 689 the species appears to have its first increase in relative abundance lower, in the uppermost Eocene (136.32 mbsf, about 39.6 Ma; see also Corliss, 1981).

Very interesting is the occurrence of assemblage 2B with common *T. alsatica*: this assemblage occurs at Site 689 as well as at the deeper (upper abyssal) Site 690, but appears to correlate well with the bathyal *T. alsatica* BB5 Zone in Berggren and Miller (1989; duration: P18-P20; Figure 12.3), instead of with their abyssal zone AB8 (duration: P18-21). All other Paleogene assemblages at the Maud Rise sites appear to correlate much better with the abyssal zones of Berggren and Miller (1989), as is common for lower bathyal sites. A similar *T. alsatica* acme zone was observed to occur at about the same time (as far as can be said from the time-resolution available) in the Indian Ocean (Schroeder-Adams, 1991), and at high northern latitudes (Kaminski et al., 1989). The latter authors describe lower Oligocene calcareous benthic faunas with *T. alsatica* above Eocene agglutinated faunas at abyssal ODP Site 747 in the Southern Labrador Sea. A *T. alsatica* Zone was not observed by Thomas (1985) in abyssal sites in the equatorial Pacific, however; possibly the species occurs over a greater depth-range at higher latitudes (both North and South) than in the equatorial regions. At Site 689 the acme of *T. alsatica* begins at 123.62 mbsf (37.09 Ma), i.e., below the increase in  $\delta^{18}\text{O}$ -values of *Cibicidoides* spp., at 122.12-

118.51 mbsf.

## DISCUSSION

Benthic foraminiferal faunal changes from middle Eocene through late Oligocene at lower bathyal Site 689 were gradual, but stepped. There were periods of faunal change alternating with stable periods, but the "periods of change" were several millions of years long: the transition between assemblages 4 and 3 lasted from about 46.7 to 44.6 Ma (2.1 m.y.), the transition from assemblage 3 to 2 lasted from about 40 to about 37 Ma (3 m.y.), and that from sub-assemblage 2B to 2A from about 34 to 31.5 Ma (2.5 m.y.). The duration of these periods of faunal change is comparable with that of the well-known middle Miocene faunal change of deep-sea benthic foraminifera (Thomas, 1985, 1986a, b; Thomas and Vincent, 1987, 1988; Miller and Katz, 1987; Boltovskoy and Boltovskoy, 1989).

During the first period of faunal change (middle middle Eocene, 46.7-44.6 Ma) large, heavily calcified *Bulimina* species and many lagenids disappeared (at least, locally); during the second period (late Eocene, 40-47 Ma) the small, smooth species *Bulimina elongata* disappeared to be replaced by *Nuttallides umbonifera* and *Turrilina alsatica*, and in the last period of faunal change (late early Oligocene, 34-31.5 Ma) *T. alsatica* became extremely rare, while *N. umbonifera* increased in relative abundance. Over the whole period the overall diversity decreased, and the relative abundance of triserial (probably infaunal) species decreased.

The timing of faunal changes at Site 689 resembles that described from many sites worldwide: there were stepped, gradual changes during the middle to late Eocene. No clear, sudden extinction event occurred at the end of the Eocene, or at the time of the sudden increase in  $\delta^{18}\text{O}$ -values in the earliest Oligocene (Corliss, 1981; Miller, 1983; Douglas and Woodruff, 1981; Corliss et al., 1984; Keigwin and Corliss, 1986; Corliss and Keigwin, 1986; Boltovskoy and Boltovskoy, 1988, 1989; Kaminski et al., 1989; Kaihu, 1991; Mackensen and Berggren, 1991; Mueller-Merz and Oberhaensli, 1991). The overall pattern of faunal change also appears to be valid worldwide (*ibidem*): in the middle Eocene (to a lesser



degree in the late Eocene), lower bathyal to upper abyssal faunas contained common to abundant elements (such as *Bulimina* species) that, in terms of modern faunas, would be considered more typical for an upper to upper-middle bathyal environment. During the middle and late Eocene the deeper faunas gradually lost these components, and from the Oligocene on the lower bathyal - upper abyssal faunas typically contained common to abundant *Nuttallides umbonifera* and *Epistominella exigua*.

There is no clear and simple correlation between the benthic foraminiferal faunal records and the records of carbon and oxygen isotopic values in benthic and planktonic foraminifers and bulk samples (Figure 12.6; see also Stott et al., 1990; Kennett and Stott, 1990; Shackleton and Hall, 1990), and between faunal records and the record of  $\text{CaCO}_3$ -content of the sediments (O'Connell, 1990). Conspicuously, there is no correlation between the lower Oligocene sudden increase in  $\delta^{18}\text{O}$ -values of benthic foraminifera and faunal change: in fact, the faunal change from assemblage 3 to 2 occurred clearly before the isotopic change at Site 689. Many authors recorded faunal changes which correspond in character to the changes at Site 689, but which occurred slightly later (at the Eocene/Oligocene boundary, i.e., still before the rapid increase in  $\delta^{18}\text{O}$  in the earliest Oligocene; e.g., Berggren and Miller, 1989; Miller, 1983; Kaminski et al., 1989). This apparent difference in timing may result from differences in stratigraphic resolution (many studies were done at lower resolution than this study). On the other hand, the difference in timing may result from problems in biostratigraphic correlation at the extremely high-latitude Site 689; the LAD of the planktonic foraminifer *Globigerinatheka index*, for instance, appears to be much earlier at Site 689 than at other high latitude sites (compare Stott and Kennett, 1990 with Berggren, 1991). The initiation of benthic foraminiferal faunal changes, however, always pre-dates the isotopic change, although some changes in relative abundance have been reported to be coeval with the isotopic change (migration of *N. umbonifera* to lesser depths; Boersma, 1985; Katz and Miller, in prep.).

This lack of correspondence in timing of fau-

nal and isotopic events supports the hypothesis that the global increase in  $\delta^{18}\text{O}$  was at least partially, and probably largely caused by ice-volume increase, not water-temperature decrease (Zachos et al., 1991). The fact that faunal change was gradual and occurred before the isotopic shift suggests that the isotopic change may indeed have been the result of a "threshold effect" (e.g., Kennett and Shackleton, 1976; Kennett, 1977). First there was gradual environmental change (cooling) until temperatures of surface waters at high latitudes reached a threshold-value, then a sudden increase in ice-volume followed (driven by positive feed-back in the system, such as increased albedo from larger ice-volume). The faunas reacted to the gradual environmental change, i.e., the gradual cooling of the waters at lower bathyal depths in the middle Eocene, when decreasing diversity mirrored increasing  $\delta^{18}\text{O}$  values of benthic foraminifera (Figure 12.6; see also Kennett and Stott, 1990; Figure 5 in Kennett and Barker, 1990); they have no reason to react to ice-volume increases on land.

At Site 689 the gradual increase in  $\delta^{18}\text{O}$  values started at about 164 mbsf (about 44.5 Ma), slightly higher than faunal change from assemblage 4 to 3 (173-165 mbsf). This time in the middle Eocene was apparently a time of many, and complex, environmental changes at Site 689. The  $\delta^{13}\text{C}$  data on bulk carbonate and *Cibicidoides* spp. (Figure 12.6; Shackleton and Hall, 1990; Kennett and Stott, 1990) show some indication that a change in surface-ocean productivity might have occurred just before the cooling: an increase in bulk-values (probably representing surface-water dissolved carbonate values) occurs at about 165 mbsf, and is not accompanied by a change in benthic values of the same magnitude; thus there may have been an increase in the surface-deep water gradients at that time. Such an increase can be explained by an increase in productivity (Shackleton, 1986; Miller and Fairbanks, 1985). There is additional evidence that there may have been an increase in surface-ocean productivity at that time: at about 160 mbsf radiolarians and diatoms first appeared (although they are rare; Thomas, unpublished data), and there is a strong and sudden increase in the abundance of radiolarians at 150 mbsf (Diester-Haass, 1991). Thus an increase in surface productivity might



have occurred in the middle Eocene before a cooling event, just as has been proposed for the early Miocene "carbon excursion," pre-dating the middle Miocene increase in oxygen isotopic values (Berger and Vincent, 1985; Thomas and Vincent, 1987). It is not clear whether this middle Eocene event occurred worldwide, or was a local, high-latitude occurrence.

A change in clay-mineral content occurs at the same levels where radiolarians and diatoms first appear in the sediments. At that level illite/smectite ratios increase, possibly indicating climatic changes on the Antarctic mainland, notably decreased hydrolysis during weathering, as a result of increased aridity or cooling (Robert and Maillot, 1990). Thus there is considerable evidence of cooling (on land), coeval with increased biosiliceous productivity in the surface waters, directly followed by cooling of oceanic surface and deep-water, starting at some time in the middle Eocene (46 Ma). The ultimate cause of these climatic and biotic changes is not clear, but it might be sought in the plate-tectonic motion of Australia northward from Antarctica, causing surface currents of colder water to reach the coasts of Maud Rise (Kennett, 1977; Kemp, 1978; Mercer, 1983; Webb, 1990).

The faunal changes may well represent the reaction of the lower bathyal faunas to cooling of the deep waters, and thus increased solubility of calcite (i.e., more difficulty in abstracting calcite by foraminifera): the disappearance of large, heavily calcified species may result from lesser availability of calcite. The strong increase in relative abundance of *N. umbonifera* probably reflects increased  $\text{CaCO}_3$ -corrosivity (Bremer and Lohmann, 1981).

One of the most important characteristics of benthic foraminiferal faunal change from middle Eocene through early Oligocene is its gradual nature: all changes occurred over several millions of years, in contrast with the benthic extinction at the end of the Paleocene, which occurred over less than 4000 years (Thomas, 1990a; 1990b; in preparation; Kennett and Stott, 1991). Faunal changes were gradual worldwide, not just on Maud Rise (references quoted above; see also Culver, 1987 for an overview). This strongly argues against the hypothesis that an overall change in direction of deep ocean circulation occurred at any time during

this interval, and against the model of development of ocean circulation as proposed by Kennett and Stott (1990). These authors proposed that Maud Rise was bathed in Warm Salty Bottom Waters (WSBW) during most of the Eocene (at least since 46 Ma), and that proto-Antarctic Bottom Waters filled the basins below the WSBW mass from the Oligocene on (pushing the WSBW to lesser depths). In this model, Site 689 was within a watermass that can be seen as a precursor of Antarctic Intermediate Water (AAIW), generated by sinking from the surface at high latitudes, whereas Site 690 was within WSBW during most of the Paleogene. The similarity between the benthic foraminiferal faunas at Sites 689 and 690 throughout the Paleogene (Thomas, 1990a) argues against the presence of two greatly different watermasses at the two sites. In addition, a circulation change must have been quick (a few thousand years at most) on a geologic time scale, as a result of the short circulation time of deep water in the oceans (Gascard, 1990). It is inconceivable that such a sudden, rapid, major change in deep and intermediate water circulation should not be reflected in large and sudden faunal changes in benthic foraminifera, in at least a few locations in the world's oceans. The observed gradual (although stepped) changes are much more likely the result of gradual cooling of deep (bathyal) waters that formed by sinking at high latitudes during the full period of middle Eocene through Oligocene. The gradual changes in the faunas then reflect gradual cooling of surface waters at high latitudes, resulting in a gradual establishment of the psychrosphere, instead of a sudden shift in the location of dominant formation of cold deep waters.

This fauna-based view of deep-water circulation can, as yet, not be made to agree with the presence of a "reversed isotope gradient" at Sites 689 and 690 (Kennett and Stott, 1990), and at the more northerly Sites 699 and 703 (Mead and Hodell, 1991). The explanation of the oxygen isotopic record, however, may be complex because salinity as well as temperature are involved, and stable density stratification may be salinity- as well as temperature-controlled (e.g., Railsback et al., 1989; Railsback, 1990). For instance, it is not easy to predict whether calcium carbonate deposited in a



WSBW mass is actually isotopically heavier or lighter than calcium carbonate deposited below a cold water mass: the WSBW is formed as a result of evaporation, leading to heavier isotopic values of the remaining water (Craig and Gordon, 1965; Railsback et al., 1989; Railsback, 1990). In addition, Site 689 is not only shallower than Site 690, but also on the opposite flank of Maud Rise. The current pattern around the rise is presently complex, with rising, less cold water masses from greater depths causing the largest polynya in the Antarctic region at the surface (Comiso and Gordon, 1987). Therefore the evidence from benthic faunal composition should be taken into account while interpreting the isotopic records.

### CONCLUSIONS

1. Lower bathyal benthic foraminiferal faunas from Maud Rise (Antarctica) show gradual, stepped faunal changes from middle Eocene through Oligocene, with steps at 46.6-44.6 Ma, 40-37 Ma, and 34-31.5 Ma (numerical ages after Berggren et al., 1985).

2. The faunal changes at Site 689 can be summarized as follows: (1) decreasing diversity and increasing relative abundance of epifaunal species, combined with the loss of large, heavily calcified *Bulimina* species; (2) the disappearance of all *Bulimina* species and the appearance of *Turrilina alsatica*; (3) the disappearance of *T. alsatica*, resulting in faunas dominated by *Nuttallides umbonifera*.

3. These faunal changes may well reflect a gradual cooling (and thus a gradual increase in corrosiveness) of the high-latitude lower bathyal waters. The gradual nature of the lower bathyal faunal changes and the absence of catastrophic extinctions (on Maud Rise, and worldwide) suggests that the psychrosphere was established as a result of the cooling of surface waters at high latitudes, while lower bathyal waters formed by cooling and sinking at high latitudes during the full interval of middle Eocene and Oligocene. Warm, salty deep waters might have been present during this time in the deepest basins, but did not reach up into the lower bathyal reaches of Maud Rise.

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	ABYSSINIA QUADRATA	AGGLUTINANTS, OTHER	ALABAMINA DISSONATA	ALLOMORPHINA TRIGONA	ANGULODERINA EARLANDI	ANOMALINA SPISSIFORMIS	ANOMALINOIDES ACUTUS	ANOMALINOIDES PSEUDOGROSSE	ANOMALINOIDES SEMICRIBRAT	ARAGONIA ARAGONENSIS	ASTRONOTON PUSTILLUM	ASTRONOTON UMBILICATULUM	BIGENERINA NODOSARIA	BOLIVINA DECUSSATA	BOLIVINA HUNERI	BOLIVINA PSEUDOPUNCTATA	BOLIVINOIDES SP. AFF DELIC	BULIMINA ALAZANENSIS	BULIMINA CALLAHANI	BULIMINA CF. SEMICOSTATA	BULIMINA ELONGATA	BULIMINA MACILENTA	BULIMINA MICROSTATA
068.92	.	.	.	.	.	1	.	2	.	.	7	3	.	1	.	.	.	.	.	.	.	1	.
070.42	.	.	.	.	.	.	.	.	.	.	1	1	.	.	.	.	.	.	.	.	.	.	.
071.93	.	.	.	.	.	.	.	.	.	.	24	1	.	.	.	.	.	.	.	.	.	.	.
072.51	.	.	.	.	.	.	.	1	.	.	2	1	1	16	.	.	.	.	.	.	.	.	.
074.01	.	.	.	.	.	.	.	3	.	.	3	6	3	12	.	1	.	.	.	.	.	.	.
075.51	.	.	.	.	.	.	2	.	.	.	5	5	3	14	.	.	.	.	.	.	.	5	.
077.01	.	.	.	1	.	.	.	9	.	1	1	1	3	7	.	.	.	.	.	.	.	.	.
078.51	.	.	.	1	.	.	3	.	.	.	5	2	3	12	.	.	.	.	.	.	.	.	.
080.01	.	.	.	.	.	.	.	5	.	.	13	1	1	2	.	.	.	.	.	.	.	.	.
080.66	.	.	.	.	9	.	.	1	.	.	3	1	13	3	.	.	.	.	.	.	.	1	.
082.11	.	.	.	.	.	.	.	.	.	.	1	1	3	2	.	.	.	.	.	.	.	.	.
083.61	.	.	.	.	.	.	1	.	.	.	35	1	2	2	.	.	.	.	.	.	1	3	2
085.11	.	.	.	.	.	.	.	.	.	.	7	7	9	.	2	.	.	.	.	.	.	.	.
086.61	.	.	.	.	.	.	.	1	.	.	2	2	9	.	.	.	.	.	.	.	.	43	.
088.11	.	.	.	.	.	.	.	.	.	.	.	2	12	.	.	.	.	.	.	.	.	.	.
089.61	.	.	.	3	.	.	.	4	.	.	4	6	10	.	.	.	.	.	.	.	.	1	.
090.49	.	.	.	.	.	.	.	7	.	.	3	3	12	.	.	.	.	.	.	.	1	.	.
091.72	.	.	.	.	.	.	.	.	.	.	4	.	6	.	.	.	.	.	.	.	.	.	.
093.22	.	.	.	1	.	.	.	.	1	.	5	5	.	6	.	.	.	.	.	.	.	1	.
094.72	.	.	.	.	.	.	.	.	.	.	5	5	.	.	.	.	.	.	.	.	.	.	.
096.22	.	.	.	.	.	.	.	1	.	.	7	7	3	.	.	.	.	.	.	.	.	.	.
097.72	.	.	.	.	.	.	.	.	.	.	3	3	.	.	.	.	.	.	.	.	.	.	.
098.96	.	.	.	.	.	.	.	1	.	.	3	2	.	.	.	.	.	.	.	.	1	.	.
101.41	.	.	.	1	.	.	.	.	.	.	3	31	.	.	.	.	.	.	.	.	.	.	.
102.91	.	.	.	1	.	.	.	.	.	.	32	1	.	.	.	.	.	.	.	.	.	.	.
104.41	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
105.91	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1
107.41	.	.	.	5	.	.	.	17	.	.	1	2	2	.	.	.	.	.	.	.	.	.	.
108.91	.	.	.	1	.	1	.	1	.	.	1	2	1	.	.	.	.	.	.	.	.	.	.
110.60	.	.	.	1	.	.	.	.	.	.	3	.	.	.	.	.	.	.	.	.	.	.	.
111.11	.	.	.	1	.	.	.	.	.	.	5	.	8	.	.	.	.	.	.	.	.	.	.
112.51	.	.	.	2	.	.	.	.	.	.	29	.	.	.	.	.	.	.	.	.	.	.	.
114.01	.	.	.	1	.	3																	



TABLE 12.1B

[illegible]



TABLE 12.1C

[illegible]



ID	NONION HAVANENSE	NONIONELLA LABRADORICA	NONIONELLA ROBUSTA	NUTTALLIDES SP., HIGH	NUTTALLIDES TRUEHMYI	NUTTALLIDES UMBONIFERA	OPHTHALMIDIUM PUSILLUM	ORIODORSALIS TENER	ORIODORSALIS UMBONATUS	OSANGULARIA INTERRUPTA	PLEUROSTOMELLA SP.	PLEUROSTOMELLIDS, OTHER	POLYMORPHINIDS	PSEUDOPARRELLA SP.	PULLENTIA BULLOIDES	PULLENTIA QUADRILOBATA	PULLENTIA QUINQUELOBA	PULLENTIA SALISBURVI	PULLENTIA SUBCARINATA	PYRAMIDINA RUDDITA	QUADRIMORPHINA ALLOMORPHI	QUINQUELOCULINA SPP.	REUSSSELLA TORTUOSA	SIGMOIDILINA TENUISS	SIPHONENERINOIDES BREVIS(SP)	SIPHONENERINOIDES ELEGANT
1						109		6	2		2				1		3	2								
2						178		1			1				2											
3						131		3	4		6				1											
4						147		6	1		4				4											
5						103		22	12		2			1												
6						159																				
7						104		1			1															
8						32		2	6		2															
9						130		2	2		2															
10						99		1			2															
11						98		2	8		2															
12						79		7	10		2															
13						60		2	16		9															
14						67		5	12		3	1		1												
15						138		4	18		1															
16						38		9	15		4															
17						101		10	4																	
18						124			9		1			1												
19						49			30		6	1														
20						15			10		13	1														
21						69		2	2		4															
22						100		2			8			8												
23						49		14	5		6	1														
24						150			5		1			2												
25						93		2	3		6			6												
26						77		8	5		5			3												
27						8					5			2												
28						110		1			3			2												
29						105			2		2			1												
30						45			7		4		1													
31						81			1		4															



TABLE 12.1E

SIPHOTEXTULARIA SPP.	SPIROPLECTAMMINA SPECTABILIS	STAINFORTHIA COMPLANATA	STILOSTOMELLA ACULEATA	STILOSTOMELLA ANNULIFERA	STILOSTOMELLA CONSCORINA	STILOSTOMELLA SP., SMOOTH	STILOSTOMELLA SUBSPINOSA	TAPPANINA SELWENSIS	TEXTULARIA ALABAMENSIS	TEXTULARIA SP.	TRITAXIA GLOBULIFERA	TROCHAMMINA GLOBIGERINIFERA	TURRILINA ALSATICA	TURRILINA BREVISPIRA	UNILOCULAR SPECIES	UNISERIAL LAGENIDS	UVIGERINA GRACILIFORMIS	UVIGERINA PEGERINA GROUP	VALVULINERIA CAMERATA	VALVULINERIA LAEVIGATA	VALVULINIA ADVENA	VALVULINIA HEXTIANA	VALVULINIA SPINOSA
5	7	...	24	...	...	...	...	...	...	...	...	...	1	...	2	4	22	4	...	...	...	...	068.92
4	2	1	38	...	...	...	...	...	...	...	...	...	1	...	2	3	1	...	...	...	...	...	070.42
1	...	...	3	...	...	...	...	...	...	...	...	...	1	...	2	2	...	...	...	...	...	...	071.93
2	2	...	15	...	...	...	...	...	...	...	...	...	2	2	3	9	1	...	...	...	...	...	072.51
...	...	...	17	...	...	...	...	...	...	...	...	...	2	2	3	1	3	1	...	...	...	...	074.01
...	...	...	3	...	...	...	...	...	...	...	...	...	2	2	4	1	23	52	...	...	...	...	075.51
...	...	...	2	...	...	...	...	...	...	...	...	...	2	2	3	4	4	...	...	...	...	...	077.01
...	...	...	4	...	...	...	...	...	...	...	...	...	2	2	1	...	56	10	...	...	...	...	078.51
...	...	...	22	...	...	...	...	...	...	...	...	...	1	...	1	4	18	...	...	...	...	...	080.01
...	...	...	8	...	...	...	...	...	...	...	...	...	...	...	2	3	7	1	...	...	...	...	080.66
...	...	...	88	...	...	...	...	...	...	...	...	...	...	...	8	4	6	2	...	...	...	...	082.11
...	...	...	2	...	...	...	...	...	...	...	...	...	...	...	15	6	...	...	...	...	...	...	083.61
...	...	...	276	6	...	...	...	...	...	...	...	...	...	...	18	3	...	...	...	...	...	...	085.11
...	...	...	1	21	61	...	...	...	...	...	...	...	...	...	13	2	...	...	...	...	...	...	086.61
...	...	...	9	62	...	...	...	...	...	...	...	...	...	...	8	3	...	...	...	...	...	...	088.11
...	...	...	32	32	...	...	...	...	...	...	...	...	...	...	9	7	...	...	...	...	...	...	089.61
...	...	...	78	...	...	...	...	...	...	...	...	...	...	...	...	4	...	19	...	...	...	...	090.49
...	...	...	1	28	...	...	...	...	...	...	...	...	...	...	4	1	...	53	...	...	...	...	091.72
...	...	...	6	10	...	...	...	...	...	...	...	...	...	...	7	5	...	...	...	...	...	...	093.22
...	...	...	34	65	...	...	...	...	...	...	...	...	...	...	11	6	...	...	...	...	...	...	094.72
...	...	...	87	48	...	...	...	...	...	...	...	...	...	...	6	4	...	...	...	...	...	...	096.22
...	...	...	60	...	...	...	...	...	...	...	...	...	...	...	5	2	3	...	...	...	...	...	097.72
...	...	...	1	34	13	...	...	...	...	...	...	...	...	...	4	6	1	...	...	...	...	...	098.94
...	...	...	10	1	...	...	...	...	...	...	...	...	...	...	1	1	7	1	...	...	...	...	101.41
...	...	...	15	...	...	...	...	...	...	...	...	...	...	...	32	2	1	8	...	...	...	...	102.91
...	...	...	4	36	6	...	...	...	...	...	...	...	...	...	17	1	1	7	1	...	...	...	104.41
...	...	...	1	11	14	...	...	...	...	...	...	...	...	...	3	6	21	4	...	...	...	...	105.91
...	...	...	8	19	34	...	...	...	...	...	...	...	...	...	3	6	1	...	...	...	...	...	107.41
...	...	...	4	43	...	...	...	...	...	...	...	...	...	...	2	5	11	15	...	...	...	...	108.91
...	...	...	6	29	40	...	...	...	...	...	...	...	...	...	3	...	...	...	...	...	...	...	110.60
...	...	...	3	1	22	...	...	...	...	...	...	...	...	...	53	1	2	...	...	...	...	...	111.01
...	...	...	33	6	...	...	...	...	...	...	...	...	...	...	118	3	...	...	...	...	...	...	112.51
...	...	...	1	...	...	...	...	...	...	...	...	...	...	...	49	11	6	...	...	...	...	...	114.01
...	...	...	2	68	...	...	...	...	...	...	...	...	...	...	93	9	2	...	...	...	...	...	115.51
...	...	...	3	1	34	...	...	...	...	...	...	...	...	...	22	5	1	...	...	...	...	...	117.01
...	...	...	3	...	26	...	...	...	...	...	...	...	...	...	44	4	1	...	...	...	...	...	118.51
...	...	...	3	...	3	...	...	...	...	...	...	...	...	...	23	4	4	...	...	...	...	...	120.20
...	...	...	...	...	30	...	...	...	...	...	...	...	...	...	78	6	1	...	...	...	...	...	120.64
...	...	...	21	51	...	...	...	...	...	...	...	...	...	...	11	4	7	...	...	...	...	...	122.12
...	...	...	4	...	25	...	...	...	...	...	...	...	...	...	7	5	8	...	...	...	...	...	123.62
...	...	...	8	...	4	...	...	...	...	...	...	...	...	...	4	6	...	...	...	...	...	...	125.12
...	...	...	65	...	4	...	...	...	...	...	...	...	...	...	16	11	...	...	...	...	...	...	126.62
...	...	...	29	6	13	...	...	...	...	...	...	...	...	...	7	22	...	...	...	...	...	...	128.12
...	...	...	46	5	6	...	...	...	...	...	...	...	...	...	8	6	1	1	...	...	...	...	129.76
...	...	...	1	34	15	...	...	...	...	...	...	...	...	...	3	11	4	14	...	...	...	...	130.32
...	...	...	16	7	54	...	...	...	...	...	...	...	...	...	7	8	3	26	...	...	...	...	131.82
...	...	...	1	8	4	...	...	...	...	...	...	...	...	...	13	41	...	...	...	...	...	...	133.32
...	...	...	6	...	5	...	...	...	...	...	...	...	...	...	4	14	...	...	...	...	...	...	134.82
...	...	...	1	63	...	...	...	...	...	...	...	...	...	...	2	...	...	...	...	...	...	...	136.32
...	...	...	17	2	17	...	...	...	...	...	...	...	...	...	12	12	...	...	...	...	...	...	137.82
...	...	...	91	...	11	...	...	...	...	...	...	...	...	...	9	13	...	...	...	...	...	...	139.40
...	...	...	77	...	5	...	...	...	...	...	...	...	...	...	6	15	...	...	...	...	...	...	139.81
...	...	...	72	...	9	...	...	...	...	...	...	...	...	...	8	19	...	...	...	...	...	...	141.31
...	...	...	47	12	...	...	...	...	...	...	...	...	...	...	12	13	...	...	...	...	...	...	142.81
...	...	...	38	...	3	...	...	...	...	...	...	...	...	...	13	9	...	...	...	...	...	...	144.31
...	...	...	3	...	7	...	...	...	...	...	...	...	...	...	12	8	...	...	...	...	...	...	145.81
...	...	...	16	...	...	...	...	...	...	...	...	...	...	...	11	11	...	...	...	...	...	...	147.31
...	...	...	2	...	7	...	...	...	...	...	...	...	...	...	6	11	...	...	...	...	...	...	148.81
...	...	...	1	...	...	...	...	...	...	...	...	...	...	...	4	9	...	...	...	...	...	...	149.09
...	...	...	1	2	13	...	...	...	...	...	...	...	...	...	6	13	...	...	...	...	...	...	149.51
...	...	...	6	...	3	...	...	...	...	...	...	...	...	...	3	9	...	...	...	...	...	...	151.01
...	...	...	6	...	3	...	...	...	...	...	...	...	...	...	4	8	...	...	...	...	...	...	152.51
...	...	...	22	6	...	...	...	...	...	...	...	...	...	...	6	3	...	...	...	...	...	...	154.01
...	...	...	34	8	2	...	...	...	...	...	...	...	...	...	9	5	...	...	...	...	...	...	155.51
...	...	...	4	...	8	...	...	...	...	...	...	...	...	...	4	10	...	...	...	...	...	...	157.01
...	...	...	4	1	...	...	...	...	...	...	...	...	...	...	9	9	...	...	...	...	...	...	158.51
...	...	...	6	...	12	...	...	...	...	...	...	...	...	...	3	12	...	...	...	...	...	...	158.80
...	...	...	5	...	3	...	...	...	...	...	...	...	...	...	4	6	...	...	...	...	...	...	159.20
...	...	...	1	...	...	...	...	...	...	...	...	...	...	...	4	2	...	...	...	...	...	...	160.70
...	...	...	8	...	...	...	...	...	...	...	...	...	...	...	7	5	...	...	...	...	...	...	162.20
...	...	...	8	...	7	...	...	...	...	...	...	...	...	...	2	18	...	...	...	...	...	...	163.70
...	...	...	...	...	34	...	...	...	...	...	...	...	...	...	15	8	...	...	...	...	...	...	165.20
...	...	...	...	...	4	...	...	...	...	...	...	...	...	...	6	10	...	...	...	...	...	...	166.85
...	...	...	7	5	11	...	...	...	...	...	...	...	...	...	8	10	...	...	...	...	...	...	167.31
...	...	...	7	2	14	...	...	...	...	...	...	...	...	...	2	9	...	...	...	...	...	...	168.81
...	...	...	6	2	...	...	...	...	...	...	...	...	...	...	7	5	...	...	...	...	...	...	170.31
...	...	...	4	5	11	...	...	...	...	...	...	...	...	...	1	12	...	...	...	...	...	...	171.81
...	...	...	58	12	10	...	...	...	...	...	...	...	...	...	4	17	...	...	...	...	...	...	173.31
...	...	...	1	...	3	...	...	...	...	...	...	...	...	...	10	20	...	...	...	...	...	...	174.81
...	...	...	21	...	41	...	...	...	...	...	...	...	...	...	3	16	...	...	...	...	...	...	177.05
...	...	...	11	...	28	...	...	...	...	...	...	...	...	...	2	15	...	...	...	...	...	...	178.52
...	...	...	14	...	76	...	...	...	...	...	...	...	...	...	2	12	...	...	...	...	...	...	180.02
...	...	...	8	...	9	...	...	...	...	...	...	...	...	...	2	12	...	...	...	...	...	...	181.52
...	...	...	9	...	12	...	...	...	...	...	...	...	...	...	2	8	...	...	...	...	...	...	183.02
...	...	...	1	...	68	...	...	...	...	...	...	...	...	...	2	22	...	...	...	...	...	...	184.46
...	...	...	4	...	15	...	...	...	...	...	...	...	...	...	9	14	...	...	...	...	...	...	188.22
...	...	...	1	...	10	...	...	...	...	...	...	...	...	...	14	25	...	...	...				