

REVISED PALEOGENE PLANKTONIC FORAMINIFERAL BIOZONATION FOR THE AUSTRAL REALM

BRIAN T. HUBER¹ and FRÉDÉRIC QUILLÉVÉRÉ²

ABSTRACT

A major revision to the Antarctic Paleogene planktonic foraminifer biozonation is presented using the latest species concepts and biostratigraphic studies of Ocean Drilling Program (ODP) sites located between 52°S and 65°S paleolatitude in the southern South Atlantic and southern Indian Oceans. Shorthand prefixes for the Antarctic Paleogene zones are designated as “AP” zones for the “Antarctic Paleocene”, “AE” zones for the “Antarctic Eocene”, and “AO” zones for the “Antarctic Oligocene”. New numerical ages for Paleogene planktonic foraminiferal and calcareous nannofossil first- and last-occurrence events are estimated using new age-depth curves constructed for ODP Sites 738 and 744 in the southern Indian Ocean. The order and timing of these events are compared with bio-, magneto- and chemostratigraphic datums that have been recently published, reinterpreted, or observed in the present study. The revised zonal framework and age models will improve correlation of Paleogene planktonic foraminifer pelagic and hemipelagic carbonate sequences within and outside the Austral Realm.

INTRODUCTION

The first zonal scheme developed for correlation of Antarctic Paleogene (AP) planktonic foraminifer assemblages was based on Stott and Kennett's (1990) study of well-preserved and comparatively continuous faunal successions obtained from ODP Sites 689 and 690 on Maud Rise, which are located in the Weddell Sea. Cross-latitude correlation of bioevents used to define the original AP zonation was afforded by a magnetic reversal stratigraphy that was constructed for those sites (Speiss, 1990; Hamilton, 1990), though some of those original interpretations have subsequently come into question (e.g., Aubry and others, 1996; Ali and others, 2000; Florindo and Roberts, 2005). The AP zonal scheme was applied, with some minor modifications, in the first biostratigraphic investigations of Paleogene planktonic foraminifer assemblages from Kerguelen Plateau (Huber, 1991a, b; Berggren, 1992). However, subsequent updates of the Paleogene biostratigraphy of Southern Ocean sites (e.g., Quillévéré, 2000; Quillévéré and others, 2001, 2002; Shipboard Scientific Party, 2000; Kelly, 2002) and revisions to the taxonomy of Paleogene planktonic foraminifera (Olsson and others, 1999; Pearson and others, in

press) have revealed that a significant revision of the AP zonation is needed in order to provide a more reliable framework for correlation between the Southern Ocean deep sea sites.

The revised Antarctic biozonation proposed herein incorporates previously recognized and new planktonic foraminifer datum events that are judged to be consistently identifiable throughout the circum-Antarctic region. The new zonal scheme is based principally on reanalysis of species distributions at ODP Site 738 (Kerguelen Plateau) and correlation with species ranges documented at seven ODP sites in the southern South Atlantic and seven sites in the southern Indian Ocean, all between 52°S and 65°S paleolatitude (Figs. 1, 2). Identifications of zonal marker taxa are based on the taxonomy of Olsson and others (1999), Pearson and others (in press) and Spezzaferri (1994). To maintain nomenclatural consistency with the revised tropical Eocene and Oligocene biozonation (“E-zones” and “O-zones”; Berggren and Pearson, 2005, this issue) the “AP” notation is herein revised to represent “Antarctic Paleocene” zones, and we designate “AE” and “AO” zones in reference to “Antarctic Eocene” and “Antarctic Oligocene” biozones, respectively.

As is characteristic of low-latitude assemblages, species diversity in circum-Antarctic faunal successions increases through the Paleocene, reaching a maximum during the latest Paleocene and early Eocene, and gradually declines from the middle Eocene through Oligocene. Yet with the exception of the early Paleocene, the high-latitude Paleogene assemblages bear little similarity to contemporaneous assemblages from low latitudes, as the most dominant and biostratigraphically useful low-latitude species are either absent or significantly diachronous in their austral high-latitude occurrences. Similarly, the dominant elements of austral assemblages tend to be absent or rare and sporadic in their low-latitude distributions. Thus, chronostratigraphic correlation of the Antarctic zonal boundaries with the tropical to subtropical zonal scheme of Berggren and Pearson (2005) is achieved by integrating magneto-, bio-, and chemostratigraphic data from several high-latitude sites for the construction of new age-depth curves. These age estimates are reported relative to the time scale of Berggren and others (1995).

CIRCUM-ANTARCTIC PALEOGENE STRATIGRAPHY

The principal sites used as the basis for revision of the Antarctic Paleogene biozonation include ODP Leg 113 Sites 689 and 690 on Maud Rise (65°S) and ODP Leg 119 and 120 sites 738, 744, 747, 748 and 749 on Kerguelen Plateau (56–62°S). A brief overview of the stratigraphy of these sites is presented below. Species distributions were also compared with published data for ODP Leg 114 sites in the southern South Atlantic (Sites 698, 699, 700, 702, 703; Nocchi and others, 1991) and Leg 183 sites on Kerguelen Pla-

¹ Department of Paleobiology, MRC 121, Smithsonian Museum of Natural History, Washington, D.C. 20013-7012, USA. E-mail: huberb@si.edu

² Laboratoire “PaléoEnvironnements & PaléobioSphère”, UMR CNRS 5125, Université Claude Bernard-Lyon 1, 27-43 Boulevard de 11 Novembre 1918, 69622 Villeurbanne cedex, France. E-mail: frederic.quillevere@univ-lyon1.fr

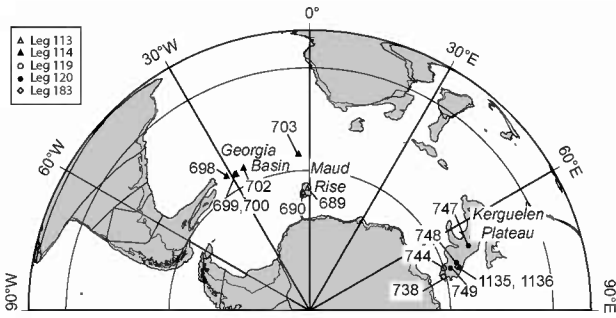


FIGURE 1. Paleogeographic reconstruction for 40 Ma (after <http://www.odsn.de/odsn/services/paleomap/paleomap.html>) showing location of circum-Antarctic ODP sites discussed in this study.

teau (Sites 1135, 1136; Coffin and others, 2000; Arney and Wise, 2003). The paleogeographic locations of these sites are shown in Figure 1 and the Paleogene lithostratigraphy for each site and denotation of intervals that have been magnetostratigraphically calibrated are presented in Figure 2. Details regarding the location, water depth, core recovery, and microfossil preservation at each of these sites are provided in the ODP Initial Reports volumes for the respective drill legs (Barker and others, 1989; Ciesielski and others, 1988; Barron and others, 1988; Coffin and others, 2000).

ODP Sites 689 and 690 yield a nearly continuous composite pelagic carbonate record from the Cretaceous/Paleogene (K/P) boundary through the upper Oligocene (Barker and others, 1988), with only a short interval in the lower Eocene missing at both sites. Subsequent to the study of Stott and Kennett (1990), higher resolution planktonic foraminifer biostratigraphic studies have been published for the Paleocene of Site 690 (Quillévére and others, 2002) and for

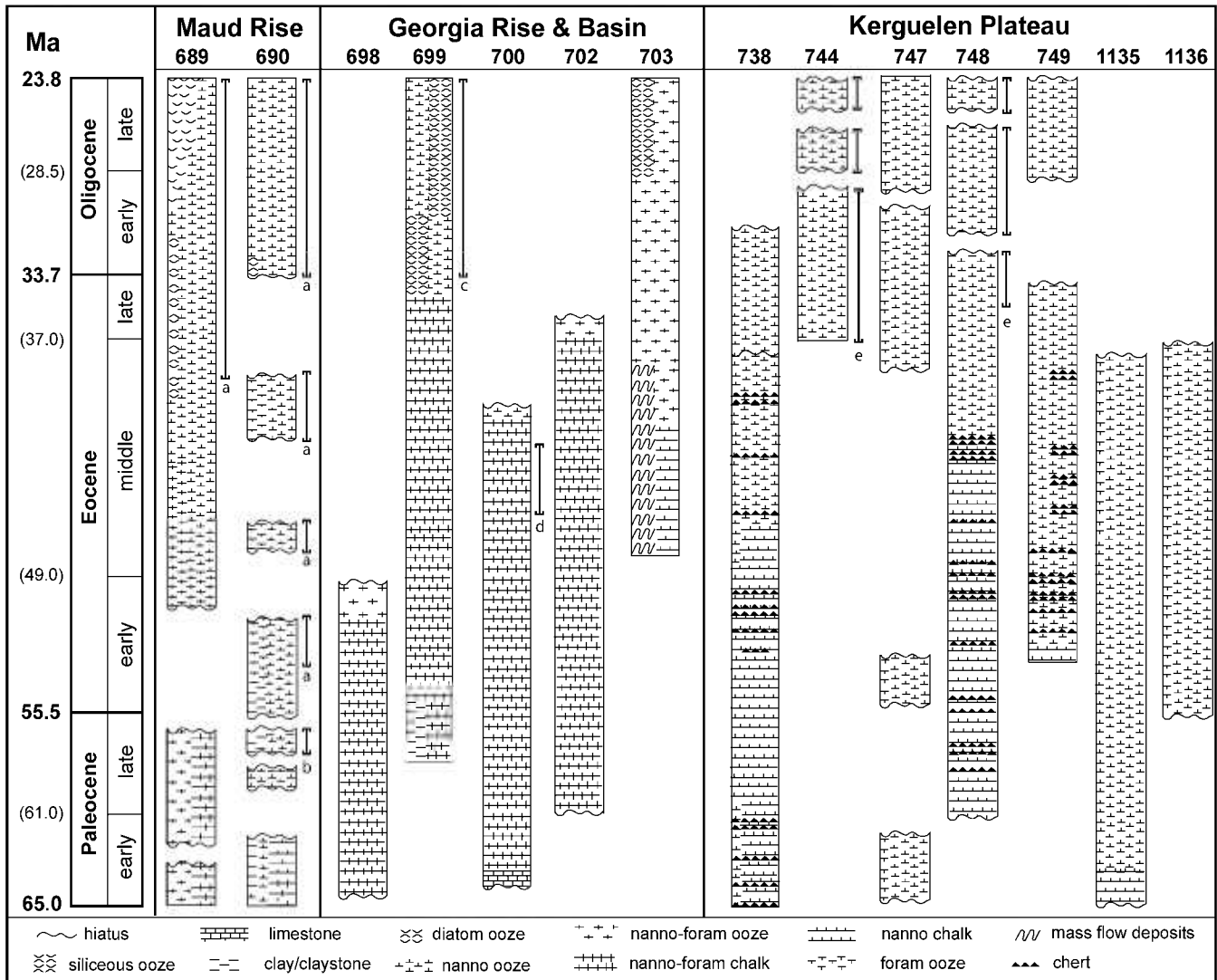


FIGURE 2. Stratigraphy of circum-Antarctic ODP sites with chronostratigraphic reinterpretation based on this study. See Figure 1 for site locations. Vertical bars with letter designations represent intervals that have been magnetostratigraphically calibrated; publication sources are shown for the following letter designations: a = Florindo and Roberts, 2005; b = Ali and others, 2000; c = Hailwood and Clement, 1991; d = Clement and Hailwood, 1991; e = Roberts and others, 2003. See text for references to site reports. See ODP site reports referenced in text for explanation of lithostratigraphy.

the Paleocene-Eocene boundary interval of Site 690 (Kelly, 2002). The magnetic polarity stratigraphy of Site 690 is based on the work of Spiess (1990) and the revised interpretations of Ali and others (2000) for the Paleocene interval.

The most complete Paleogene record obtained from Kerguelen Plateau was drilled at the southernmost site, ODP Site 738, where a lower Paleocene-lower Oligocene section ranging from ~17–377 mbsf (meters below seafloor) was recovered (Figs. 1, 2). Core recovery was nearly complete in the upper Eocene to lower Oligocene interval, moderate in the middle Eocene, and poor to moderate in the Paleocene to lower Eocene interval (Barron and others, 1989). Other than a hiatus that spans calcareous nannofossil Zone CP14b within the middle Eocene (Fig. 2), the Paleocene to lower Oligocene record from this site was judged to be biostratigraphically complete (Wei and Thierstein, 1991; Huber, 1991a, b). Relative abundance estimates of moderately to well-preserved planktonic foraminifera were obtained at relatively low resolution (~1 sample/1.5 m) for the Cretaceous through Neogene by Huber (1991a, b), and abundance counts were made for the Paleocene-Eocene boundary interval by Lu and Keller (1993). The shipboard magnetic polarity stratigraphy for this site was considered ambiguous (Barron and others, 1989), and no new magnetostratigraphic data from Paleogene sediments recovered at this site have been published subsequent to the shipboard study.

Less complete Paleogene pelagic carbonate sequences from Kerguelen Plateau were cored at Sites 744, 747, 748 and 749. The lithostratigraphy and distribution of hiatuses are shown in Figure 2. Low-resolution biostratigraphic studies of well-preserved planktonic foraminifera and calcareous nannofossils have been published for each of these sites (Huber, 1991b; Wei and Thierstein, 1991; Berggren, 1992; Aubry, 1992). Shipboard magnetostratigraphic interpretations for Sites 744 and 748 have been superseded by the higher resolution study of Roberts and others (2003), who developed a new age model using correlation with published nannofossil and planktonic foraminifer datums and strontium isotope data. These authors provide the basis for determining the extent of several of the hiatuses shown in Figure 2.

SITE 738 AGE-DEPTH PROFILE

An age-depth curve is constructed for the Paleogene sequence of Site 738 (Fig. 3) using calcareous nannofossil and planktonic foraminifer datums that have been previously calibrated using paleomagnetic control. These are marked in bold and referenced in Table 1. The datum levels represent the midpoint between the sample containing the datum marker and the next sample below or above where the datum marker is absent, and are based on biostratigraphic data reported for nannofossils by Wei and Thierstein (1991) and for planktonic foraminifera by Huber (1991a, b), as well as observations from the present study. Additional datums that provide reliable tie points for the age-depth curve include the carbon isotope excursion (CIE), which is used to identify the Paleocene/Eocene boundary, and the calcareous plankton mass extinction, which is used to identify the Cretaceous/Paleogene (K/P) boundary.

Two unconformities are recognized in the Paleogene sequence of Site 738. A ~25-m.y. unconformity identified at ~18.17 mbsf separates lower Oligocene sediments estimated at 33.0 Ma from upper Miocene sediments. The second unconformity is placed at ~70.59 mbsf and is estimated to span between 36.8 and 38.8 Ma. The remaining intervals of the Paleogene section are judged to be continuous, with sedimentation rates ranging between a maximum of 14.3 m/m.y. in the middle Eocene to less than 4.5 m/m.y. in the lowermost Danian (Fig. 3).

On the basis of the Site 738 age-depth curve, new age estimates for nannofossil and planktonic foraminifer datums (Table 1) are calculated for previously calibrated datum events and for highest and lowest occurrences of biostratigraphically important nannofossil and foraminifer species that have not been paleomagnetically calibrated (Table 1). Age estimates for planktonic foraminifer species whose highest and lowest occurrences are used to define zonal boundaries for the revised Antarctic Paleogene zonal scheme used in this study are also presented in Table 1 and are cited in the next section.

ANTARCTIC PALEOGENE BIOZONATION

Below we present a planktonic foraminiferal zonal scheme for the Antarctic Paleogene that has been significantly modified from that of Stott and Kennett (1990). These are designated with the new short-hand prefixes “AP”, “AE” and “AO” zones to represent the “Antarctic Paleocene”, “Antarctic Eocene” and “Antarctic Oligocene” zones, respectively. Age estimates for zonal datums that have not been paleomagnetically calibrated (i.e., estimated) are designated below with an “approximately” (~) symbol, and are based on the age model developed for Site 738 (see above for explanation; Table 1). Reference sources for the zonal datums that have been paleomagnetically calibrated and their ages are presented in Table 2.

In the discussion below we differentiate between lowest (LO) and highest (HO) occurrences of marker species used to define biozone boundaries, and first-appearance (FAD) and last-appearance (LAD) datums used to define the temporal limits of a bioevent. When stratigraphic sections are continuous, the LO and HO of a taxon are also equal to the FAD and LAD of the taxon (Aubry, 1995; Berggren and others, 2000). Thus, the biozone is converted into a chronozone whose boundaries record the FAD and LAD of the nominate taxon/taxa.

We adopt the naming convention for five categories of interval zones as described by Berggren and Pearson (2005).

ANTARCTIC PALEOCENE (AP) BIOZONATION

AP0. *Guembelitra cretacea* Partial-range Zone (herein defined; different denotation than Smit [1982] and Keller [1988]).

Definition: Biostratigraphic interval characterized by the partial range of the nominate taxon from the HO of Cretaceous planktonic foraminifera (e.g., *Abathomphalus*, *Globotruncana*, *Rugoglobigerina*, *Globigerinelloides*) to the LO of *Globoconusa daubjergensis* (Fig. 4).

Magnetostratigraphic calibration: At ODP Hole 690C, the LO of *G. daubjergensis* was recorded in the late part of Chron C29r (Hamilton, 1990).

Estimated age: Base 65.00, top ~64.76 Ma; earliest Paleocene (Fig. 5, Table 2).

Remarks: Although *G. cretacea* was rare during the late Maastricht-

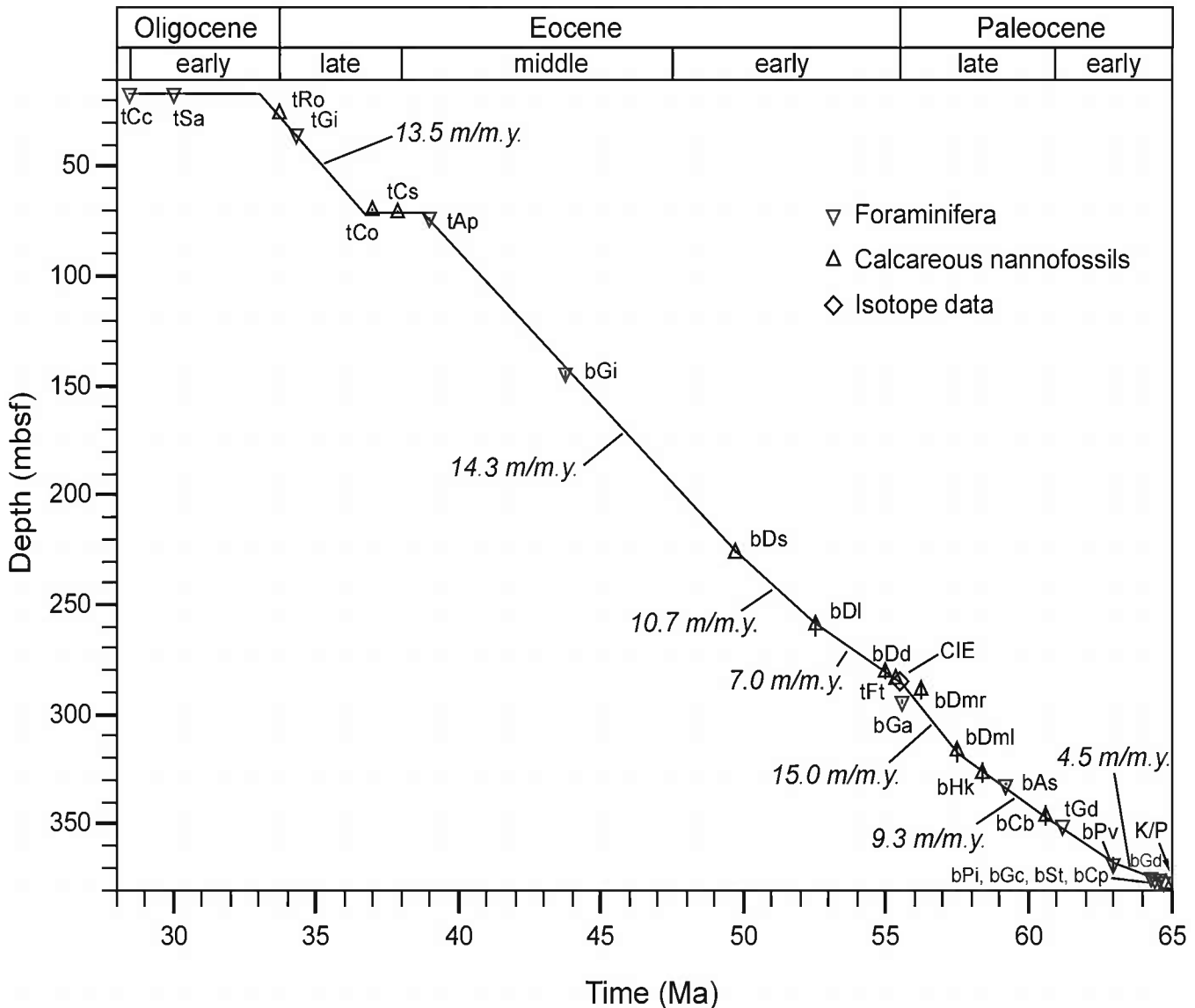


FIGURE 3. Paleocene through early Oligocene age-depth curve constructed for ODP Site 738 based on reliable planktonic foraminifer and calcareous nannofossil geochemical datums. Sedimentation rates calculated from this age model are in italics. Datum labels abbreviated for b = base or t = top followed by upper-case first letter of genus and lower case first letter of species are listed in bold in Table 1. Vertical bars within symbols represent depth errors (see Table 1 for explanation). CIE = carbon isotope excursion. Age-depth model created using the *CHRONOS* ADP application (see <http://www.chronos.org>).

tion, its abundance dramatically increased immediately following the K/P boundary event in the open ocean, and it became a cosmopolitan taxon (see Olsson and others, 1999). *Guembelitria cretacea* is abundant in the lowermost Danian sediments recovered from ODP Sites 690, 738 and 747, where it ranges throughout Zone AP0 and Subzone AP1a.

Zone AP0, as defined herein, is not an equivalent of Stott and Kennett's (1990) Zone AP α (see Fig. 5). These authors defined AP α as the *Eoglobigerina fringa* Partial Range Zone from the HO of *A. mayaroensis* to the initial common occurrence of *Subbotina pseudobulloides* (i.e., *Parasubbotina pseudobulloides*, following Olsson and others, 1999). *Eoglobigerina fringa* is an ambiguous taxon since it may be a senior synonym for *E. eobulloides* (e.g., Olsson and others, 1999). To distinguish the top of AP0, we used the morphologically very distinctive *Globoconusa daubjergensis* to avoid ambiguities in the stratigraphic delineation of an initial "common" occurrence. The LO of *G. daubjergensis* occurs ~0.2 m above the K/P boundary at ODP Hole 690C (this work), ~0.4 m above the K/P boundary at ODP Site 738 (Huber, 1991a), and ~1 m above the K/P boundary at ODP

Holes 747A and 747B (Berggren, 1992). Based on the temporal interpretation of the sediments recovered at ODP Hole 690C (Quillévére and others, 2002), we estimate the LO of *G. daubjergensis* at 64.76 Ma. This is in good agreement with the age estimate of 64.84 Ma at Site 738 (Table 1) and is essentially the same age as the base of Zone P1a in the revised tropical/subtropical zonation of Berggren and Pearson (2005).

AP1. *Globoconusa daubjergensis* Taxon-range Zone (herein defined).

Definition: Biostratigraphic interval characterized by the total range of the nominate taxon (Fig. 4).

Magnetostratigraphic calibration: See above for magnetostratigraphic calibration of the LO of *G. daubjergensis*. No magnetostratigraphic data are available to calibrate the HO of *G. daubjergensis* (but see below).

Estimated age: Base 64.76, top 61.20 Ma; earliest Paleocene (Danian; Fig. 5, Table 2).

Remarks: We estimate the LO of *G. daubjergensis* at 64.76 Ma (see

TABLE 1. Calibrated and estimated datums for planktonic foraminifera (Huber, 1991a, b; this study) and calcareous nanofossils (Wei and Thierstein, 1991) from ODP Site 738. "Calib. Age" refers to datum age calibrations based on previously published radiometric and/or paleomagnetic tie points; "Est. Ages" refer to ages interpolated between calibrated datum tie points (listed in bold) using the age-depth curve constructed for Site 738 (see Figure 3). LAD = Last Appearance Datum; FAD = First Appearance Datum; type refers to datum type; PF = planktonic foraminifera; N = nanofossil; CIE = Carbon Isotope Excursion; G = geochemical; MECO = Mid-Eocene Climatic Optimum. Asterisks in the sample column refer to planktonic foraminifera datums determined during this study; "Top Depth" and "Bot. Depth" refer to the depths in meters below seafloor (mbsf) for the sample containing the datum and the next sample studied above or below that datum level; "Depth Error" refers to the difference in meters between those two samples and "Midpt. Depth" refers to the mbsf depth between those two samples; "unconf." refers to unconformity. Ages in million years; depths in meters and meters below seafloor.

Datum	Species datum	Type	Sample	Top depth (mbsf)	Bot. depth (mbsf)	Depth error (m)	Midpt. depth (mbsf)	Calib. age (Ma)	Est. ages (Ma)
LAD	<i>Chilouembelina cubensis</i>	PF	738B-3H-4, 90-95	17.80	18.53	0.73	18.17	28.50 ^a	unconf.
LAD	<i>Subbotina angiporoides</i>	PF	738B-3H-4, 90-95	17.80	18.53	0.73	18.17	30.00 ^a	unconf.
LAD	<i>Reticulofenestra oamaruensis</i>	N	738B-4H-2, 66-68	25.16	26.66	1.50	25.91	33.70 ^a	33.64
LAD	<i>Subbotina eocena</i>	PF	738B-4H6, 90-95	29.90	31.40	1.50	30.65	34.30 ^a	38.89
LAD	<i>Globigerinatheka index</i>	PF	738B-5H-3, 90-95	34.90	36.40	1.50	35.65		34.28
LAD	<i>Tenuitella insolita</i>	PF	738B-5H-4, 90-95	36.40	37.90	1.50	37.15		34.49
FAD	<i>Tenuitella insolita</i>	PF	738B-6H-6, 84-89	50.34	51.50	1.16	50.92		35.54
LAD	<i>Acarinina medizczi</i>	PF	738B-7H-2, 90-95*	52.40	53.90	1.50	53.15	37.70	35.67
LAD	<i>Acarinina collactea</i>	PF	738B-7H-2, 90-95	52.40	53.90	1.50	53.15	37.70 ^a	35.67
LAD	<i>Subbotina linaperta</i> s.s.	PF	738B-7H-CC	59.90	61.00	1.10	60.45	37.70 ^a	unconf.
FAD	<i>Reticulofenestra bisecta</i>	N	738B-8H-3, 66-68	63.16	64.66	1.50	63.91	38.00 ^a	unconf.
FAD	<i>Chiasmolithus oamaruensis</i>	N	738B-8H-CC	69.09	70.59	1.50	69.84	37.00 ^a	unconf.
LAD	<i>Chiasmolithus solitus</i>	N	738B-9H-1, 66-68	70.59	71.16	0.57	70.88	37.90 ^b	unconf.
LAD	<i>Acarinina primitiva</i>	PF	738B-9H-3, 90-95	72.90	74.40	1.50	73.65	39.00 ^a	39.06
LAD	MECO peak ^c	G	738B-11H-6, 35-37	92.85	92.85		92.85		40.41
FAD	<i>Subbotina angiporoides</i>	PF	738B-14X-CC*	118.70	121.70	3.00	120.20		42.33
LAD	<i>Nannotetrina fulgens</i>	N	738B-17X-5, 36-38	142.36	143.56	1.20	142.96	43.10 ^a	43.92
FAD	<i>Globigerinatheka index</i>	PF	738B-17X-5, 30-35	143.50	146.80	3.30	145.15	43.70 ^d	44.08
FAD	<i>Subbotina eocena</i>	PF	738B-20X-4, 90-95	171.60	175.80	4.20	173.70		46.08
LAD	<i>Globanomalina australiformis</i>	PF	738B-21X-CC	179.70	185.40	5.70	182.55		46.70
LAD	<i>Cassigerinelloita amekiensis</i>	PF	738B-21X-CC	179.70	185.40	5.70	182.55		46.70
LAD	<i>Acarinina bullbrooki</i>	PF	738B-21X-CC*	179.70	185.40	5.70	182.55		46.70
FAD	<i>Pseudohastigerina micra</i>	PF	738B-22X-4, 90-95	190.80	195.00	4.20	192.90		47.43
FAD	<i>Acarinina collactea</i>	PF	738C-4R-2, 85-90	218.25	219.8	1.55	219.03		49.26
FAD	<i>Discoaster subloboensis</i>	N	738C-5R-, 69-70	225.60	226.26	0.66	225.93	49.70 ^a	49.76
FAD	<i>Cassigerinelloita amekiensis</i>	PF	738C-5R-2, 73-78	227.83	235.20	7.37	231.52		50.23
FAD	<i>Acarinina primitiva</i>	PF	738C-7R-1, 88-93	245.68	247.83	2.15	246.76		51.49
FAD	<i>Discoaster lodoensis</i>	N	738C-8R-CC	255.06	264.10	9.04	259.58	52.85 ^a	52.57
FAD	<i>Acarinina pentacamerata</i>	PF	738C-8R-1, 90-95	255.30	264.10	8.80	259.70		52.59
LAD	<i>Morozovella subbotinae</i>	PF	738C-9R-1, 25-30	264.10	264.35	0.25	264.23		53.10
LAD	<i>Chilouembelina wilcoxensis</i>	PF	738C-9R-1, 25-30	264.10	264.35	0.25	264.23		53.10
FAD	<i>Triburchitius orthostylus</i>	N	738C-10R-3, 66-68	277.46	283.40	5.94	280.43	53.64 ^a	54.94
FAD	<i>Discoaster diastypus</i>	N	738C-10R-CC	283.40	283.40	0.90	283.85	55.00 ^a	55.33
LAD	<i>Fasciculithus tympianiformis</i>	N	738C-10R-CC	277.46	283.40	5.94	280.43	55.33 ^a	55.33
FAD	<i>Acarinina wilcoxensis</i>	PF	738C-10R-CC	283.40	283.40	0.90	283.85		55.33
FAD	<i>Globanomalina chapmani</i>	PF	738C-10R-CC	283.40	283.40	0.90	283.85		55.33
LAD	<i>Pseudohastigerina wilcoxensis</i>	PF	738C-11R-1, 115-118	284.55	286.05	1.50	285.30		55.45
FAD	<i>Morozovella subbotinae</i>	PF	738C-11R-2, 31-33*	285.22	285.31	0.09	285.27	55.90 ^a	55.45
FAD	<i>Morozovella subbotinae</i>	PF	738C-11R-2, 40-42*	285.31	285.35	0.04	285.33		55.90
FAD	<i>CIE^e</i>	G	738C-11R-2, 44-46	285.35	285.50	0.15	285.43	55.50	55.46
FAD	<i>Discoaster multi-radiatus</i>	N	738C-11R-CC	285.80	293.00	7.20	289.40	56.20 ^a	55.72
FAD	<i>Globanomalina australiformis</i>	PF	738C-11R-CC	293.00	295.00	2.00	294.00	55.55 ^a	56.02

TABLE 1. Continued.

Datum	Species datum	Type	Sample	Top depth (mbsf)	Bot. depth (mbsf)	Depth error (m)	Mldpt. depth (mbsf)	Calib. age (Ma)	Est. ages (Ma)
LAD	<i>Subbotina trilocalinoides</i>	PF	738C-13R-CC	312.30	321.90	9.60	317.10	56.50 ^a	57.02
FAD	<i>Globanomalina planoconica</i>	PF	738C-13R-CC	312.30	321.90	9.60	317.10		57.02
FAD	<i>Dicouster mohleri</i>	N	738C-14R-CC	312.30	321.90	9.60	317.10	57.50 ^a	57.02
FAD	<i>Heliolithus kleinpeltii</i>	N	738C-15R-CC	321.90	331.60	9.70	326.75	58.40 ^a	58.52
FAD	<i>Muricella pusilla</i>	PF	738C-15R-CC	321.90	331.60	9.70	326.75		58.52
FAD	<i>Acarinina subsphaerica</i>	PF	738C-15R-CC	331.60	332.15	0.55	331.88	59.20 ^a	59.10
FAD	<i>Acarinina mckinnai</i>	PF	738C-16R-1, 55-60	332.15	333.84	1.69	333.00		59.17
FAD	<i>Acarinina strabocella</i>	PF	738C-16R-4, 90-95*	337.00	338.50	1.50	337.75	61.00 ^b	59.67
LAD	<i>Hornibrookensis teuricensis</i>	N	738C-16R-5, 97-98	338.30	341.30	3.00	339.80	58.30 ^a	59.88
FAD	<i>Sphenolithus primus</i>	N	738C-16R-CC	338.30	341.30	3.00	339.80	60.60 ^a	59.88
LAD	<i>Fasciculithus pileatus</i>	N	738C-16R-CC	341.30	350.90	9.60	346.10		60.54
FAD	<i>Fasciculithus typaniformis</i>	N	738C-17R-CC	341.30	350.90	9.60	346.10	59.70 ^a	60.54
FAD	<i>Chiasmolithus bidens</i>	N	738C-17R-CC	341.30	350.90	9.60	346.10	60.70 ^a	60.54
LAD	<i>Globoconusa daubjergensis</i>	PF	738C-17R-CC	350.45	350.90	0.45	350.68	61.20 ^a	61.10
FAD	<i>Prinsius martinii</i>	N	738C-18R-CC	350.90	360.50	9.60	355.70	62.40 ^c	61.64
FAD	<i>Parasubbotina varianta</i>	PF	738C-19R-CC	365.00	371.22	6.22	368.11	63.00 ^a	63.09
LAD	<i>Proemurica inconstans</i>	PF	738C-20R-1, 102-104	371.22	372.88	1.66	372.05	63.23 ^d	63.83
FAD	<i>Globanomalina compressa</i>	PF	738C-20R-2, 118-120	372.88	374.10	1.22	373.49	63.23 ^d	64.19
FAD	<i>Subbotina trilocalinoides</i>	PF	738C-20R-3, 90-92	374.10	374.87	0.77	374.49	64.69 ^e	64.41
FAD	<i>Globoconusa daubjergensis</i>	PF	738C-20R-5, 56-57	376.76	376.85	0.09	376.81	64.76 ^e	64.84
FAD	<i>Cruciplacolithus primus</i>	N	738C-20R-5, 84.1	377.04	377.04	0.00	377.04	64.80 ^a	64.92
FAD	<i>Eoglobigerina ebullitoides</i>	PF	738C-20R-5, 95-96	377.15	377.16	0.01	377.16		64.99
FAD	K/P boundary^b	PF	738C-20R-5, 96.5	377.16	377.16	0.00	377.16	65.00 ^a	65.00

^a Berggren and others, 1995.^b Arney and Wise, 2003.^c Bohaty and Zachos, 2003.^d Incorrectly reported as 42.9 Ma in Berggren and others, 1995.^e Backman, 1986.^f Lu and Keller, 1993.^g Calibrated this study.^h Thierstein and others, 1991.

TABLE 2. Revised Antarctic Paleogene Zones, defining datums, and datum ages. FAD = First Appearance Datum; LAD = Last Appearance Datum; PRZ = Partial Range Zone; HOZ = Highest Occurrence Zone; TRZ = Taxon Range Zone; CRZ = Concurrent Range Zone; PRSZ = Partial Range Subzone; LOSZ = Lowest Occurrence Subzone; CRSZ = Concurrent Range Subzone.

Zone	Base Datum	Base age (Ma)
AN1	LAD <i>Globigerina euapertura</i>	23.80 ^b
AO4	LAD <i>Globigerina labiacrassata</i>	27.10 ^b
AO3	LAD <i>Chiloguembelina cubensis</i>	28.50 ^b
AO2	LAD <i>Subbotina angiporoides</i>	30.00 ^b
AO1	LAD <i>Globigerinatheka index</i>	34.30 ^b
AE10	LAD <i>Tenuitella insolita</i>	34.49 ^c
AE9	FAD <i>Tenuitella insolita</i>	35.54 ^c
AE8	LAD <i>Acarinina primitiva</i>	39.00 ^b
AE7	FAD <i>Subbotina angiporoides</i>	42.33 ^c
AE6	FAD <i>Globigerinatheka index</i>	43.70 ^b
AE5	LAD <i>Cassigerinelloita amekiensis</i>	46.70 ^c
AE4	FAD <i>Cassigerinelloita amekiensis</i>	50.23 ^c
AE3	FAD <i>Acarinina primitiva</i>	51.49 ^c
AE2	LAD <i>Chiloguembelina wilcoxensis</i>	53.10 ^c
AE1	FAD <i>Globanomalina australiformis</i>	55.55 ^d
AP4	LAD <i>Subbotina triloculinoides</i>	56.50 ^b
AP3	FAD <i>Acarinina subsphaerica</i>	59.20 ^d
AP2	LAD <i>Globoconusa daubjergensis</i>	61.20 ^d
AP1c	FAD <i>Praemurica inconstans</i> / <i>Globoconusa daubjergensis</i> CRSZ	63.23 ^d
AP1b	FAD <i>Subbotina triloculinoides</i>	64.69 ^d
AP1a	FAD <i>Eoglobigerina eobulloides</i> PRSZ	64.76 ^d
AP1	FAD <i>Globoconusa daubjergensis</i>	64.76 ^d
AP0	K/P boundary	65.00 ^b

^a Berggren, 1992.
^b Berggren and others, 1995.
^c Estimated this study (see Table 1).
^d Calibrated this study (see Table 1).

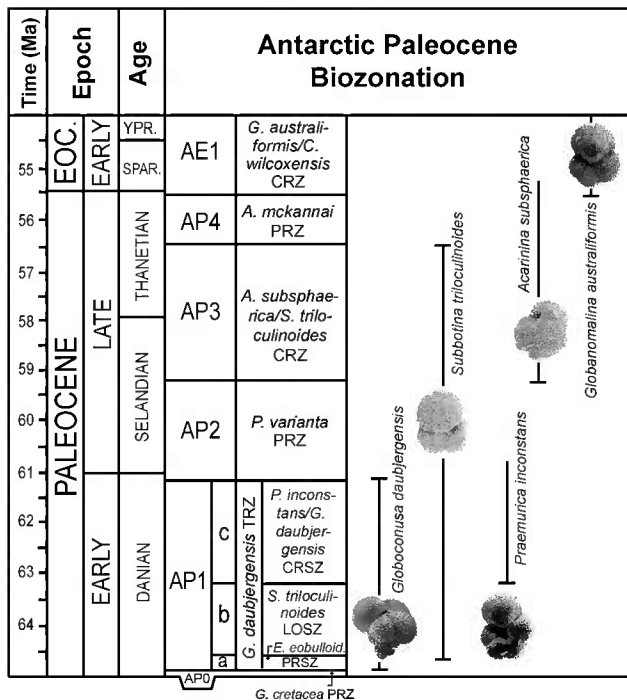


FIGURE 4. Planktonic foraminifer species used to define the new Antarctic Paleocene (AP) zones and subzones. Stratigraphic ranges are shown with horizontal lines representing zonal datum levels. Time scale based on Berggren and others (1995) with the inclusion of the Sparnacian Stage as defined by Aubry and others (2003).

above). Quillévéré (2000) and Quillévéré and others (2001) have shown that in high southern latitudes (ODP Holes 690C and 750A), the HO of *G. daubjergensis* can be used to approximate the tropical/subtropical P1/P2 zonal boundary (61.37 Ma; Berggren and others, 2000; Berggren and Pearson, 2005).

Zone AP1, as defined herein and shown in Figure 5, is not an equivalent of Stott and Kennett's (1990) and Huber's (1991a) Zone AP1. Stott and Kennett (1990) defined Zone AP1 as the *Subbotina pseudobulloides* Interval Zone between the initial "common" occurrence of *S. pseudobulloides* (i.e., *Parasubbotina pseudobulloides*, following Olsson and others, 1999) and the initial occurrence of "*Planorotalites imitatus*" (i.e., *Globanomalina imitata*, following Olsson and others, 1999). Huber (1991a) defined Zone AP1 as the *S. pseudobulloides* Partial Range Zone from the LO of *G. daubjergensis* to the LO of "*P. imitatus*". Again, the total range of the morphologically very distinctive *G. daubjergensis* was used here to avoid ambiguities in both the stratigraphic delineation of an initial "common" occurrence and in the ambiguous recognition of *G. imitata*.

Planktonic foraminiferal assemblages observed in Zone AP1, as defined here, are similar to those described from Zone P1 in low-latitude sequences (Berggren and Norris, 1997; Olsson and others, 1999). Zone AP1 is marked by the initial occurrence and/or diversification of several new trochospiral genera, including *Subbotina*, *Parasubbotina*, *Globanomalina*, and *Praemurica*. Based on the sequential appearances of *Subbotina triloculinoides*, *Globanomalina compressa* and/or *Praemurica inconstans*, Zone AP1 has been further subdivided into three subzones.

AP1a. *Eoglobigerina eobulloides* Partial-range Subzone (herein defined).

Definition: Biostratigraphic interval containing the nominate taxon from the LO of *Globoconusa daubjergensis* to the LO of *Subbotina triloculinoides* (Fig. 4).

Magnetostratigraphic calibration: At ODP Holes 690C and 738C,

PALEOCENE TIME SCALE

TIME (Ma)	CHRON	POLARITY	EPOCH	AGE	CALCAREOUS NANNO.		PLANKTONIC FORAMINIFERA							
					Martini (1971)	Bukry (1973, 1975)	Tropical		Circum-Antarctic					
							Berggren and Pearson (2005)	Stott and Kennett (1990)	This study					
54	C24r		EOC. EARLY	SPAR.	NP10	CP9	a	E4	<i>M. formosa</i> LOZ	AP6	a	AE1	<i>G. australiformis</i> / <i>C. wilcoxensis</i> CRZ	
55								E3	<i>M. marginodentata</i> PRZ	AP5				
56	C25n	n	PALEOCENE LATE	THANETIAN	NP9	CP8	b	E1	<i>P. wilcoxensis</i> / <i>M. velascoensis</i> CRZ	AP4		AP4	<i>A. mckennai</i> PRZ	
57	C25r							NP7	P4					c
58	C26n	n	NP6	a	G. <i>pseudomemardii</i> / <i>P. varicospira</i> CRSZ	AP3	M. <i>mckennai</i> IZ	AP2		P. <i>variata</i> PRZ				
59	C26r		NP5	CP4					P3		b	<i>I. albeari</i> LOSZ	AP2	P. <i>variata</i> PRZ
60	C27n	n	PALEOCENE EARLY	SELANDIAN	NP4	CP3-CP2	a	<i>I. pusilla</i> LOSZ		AP2				
61									NP4		CP3-CP2	P2	<i>P. mckennai</i> LOZ	AP2
62	C27r		DANIAN		NP3		P1	c	G. <i>compressa</i> - <i>P. inconstans</i> LOSZ	AP1	b	AP1	c	P. <i>inconstans</i> / <i>G. daubjergensis</i> CRSZ
63	C28n	n												
64	C28r		NP2	a	P. <i>pseudobulloides</i> PRSZ	AP1	a	G. <i>daubjergensis</i> PRSZ	AP1	b	S. <i>triloculinoides</i> ISZ <i>E. eobulloides</i> PRSZ			
65	C29n	n	NP1	CP1								a	P. <i>pseudobulloides</i> PRSZ	AP1
66	C29r		MAAS.			P0 & P1α	<i>P. eugubina</i> & <i>G. cretacea</i>	APα	<i>E. tringa</i> PRZ	AP0	<i>G. cretacea</i> PRZ			
66	C30n	n	CRET.											

FIGURE 5. Correlation of Antarctic Paleocene biozonation defined in this study with the original Antarctic Paleocene biozonation of Stott and Kennett (1990), the Paleocene tropical planktonic foraminiferal zonation of Berggren and others (1995), and the standard calcareous nannoplankton biostratigraphies of Martini (1971) and Bukry (1973, 1975) using the Berggren and others (1995) time scale with the inclusion of the Sparnaccian Stage as defined by Aubry and others (2003).

the LO of *G. daubjergensis* was recorded in the late part of Chron C29r (Hamilton, 1990; Huber, 1991b; Quillévéré, 2000). At ODP Hole 690C, the LO of *S. triloculinoides* was recorded in the early part of Chron C29n (Hamilton, 1990; Quillévéré, 2000).

Estimated age: Base 64.76, top 64.69 Ma; early Paleocene (Danian; Fig. 5, Table 2).

Remarks: We estimate the LO of *G. daubjergensis* at 64.76 Ma (see above). Based on the location at 247.55 mbsf of the C29n/r Magnetozone boundary at ODP Hole 690C (Hamilton, 1990), and the temporal interpretation by Quillévéré and others (2002), we calculate the LO of *S. triloculinoides* at 64.69 Ma.

Subzone AP1a is defined differently than in Stott and Kennett's (1990) zonal scheme. This was done first, to avoid ambiguities in the stratigraphic delineation of the initial "common" occurrence of *Parasubbotina pseudobulloides* (see above), and second, because we selected the LO of *S. triloculinoides* as a zonal marker for the AP1a/AP1b zonal boundary.

Subzone AP1a is marked by the common co-occurrence of *G. daubjergensis* and *E. eobulloides*, the latter taxon being very abundant throughout this subzone. Other characteristic elements include *Subbotina trivialis*, *Parasubbotina pseudobulloides*, *Praemurica taurica*, *P. pseudoinconstans*, *Globanomalina planocompressa*, *Chiloguembelina midwayensis* and *Guembelitra cretacea*. At ODP Holes 690C and 738C, *G. daubjergensis* has its LO just below that of *S. triloculinoides* (Quillévéré, 2000; Huber, 1991a). Previous stratigraphic interpretations where the LO of *G. daubjergensis* has not been observed to precede that of *S. triloculinoides* may result from: (1) low sample

density, (2) an artifact of perturbation, or (3) misidentification of *S. trivialis* for *S. triloculinoides*. The very short duration of Subzone AP1a (70 kyrs) makes it difficult to identify in deep-sea sequences because of the low early Danian sedimentation rates.

AP1b. *Subbotina triloculinoides* Lowest-occurrence Subzone (same denotation as the *Subbotina triloculinoides*-*Globanomalina compressa*/*Praemurica inconstans* Interval Subzone [P1b] of Berggren and others, 1995; see Fig. 5).

Definition: Biostratigraphic interval from the LO of the nominate taxon to the LOs of *G. compressa* and/or *P. inconstans* (Fig. 4).

Magnetostratigraphic calibration: The LO of *S. triloculinoides* is in the early part of Chron C29n at ODP Hole 690C. No magnetostratigraphic data were available to calibrate the LO of *P. inconstans*. At Hole 690C, this taxon first occurs about 10 m above the C29n/r Magnetozone boundary.

Estimated age: Base 64.69, top 63.23 Ma; early Paleocene (Danian; Fig. 5, Table 2).

Remarks: We estimate the LO of *S. triloculinoides* at 64.69 Ma (see above). At low-latitude locations, *P. inconstans* and *G. compressa* appeared simultaneously at 63.0 Ma, and the LO of the latter taxon can be used to delineate the P1b/P1c zonal boundary (Berggren and others, 1995, 2000). At ODP Holes 690C and 750A, both taxa also appeared simultaneously (Quillévéré, 2000), whereas the LO of *P. inconstans* is located just above that of *G. compressa* at Site 738 (Huber, 1991b). The LO of *P. inconstans* coincides with the HO of its ancestor *Praemurica pseudoinconstans*. Note, however, that consistent differentia-

tion between the latter species and early morphotypes of *P. inconstans* is difficult because of their morphologic similarity. As is done at low latitudes, the LO of *G. compressa*, which is easier to differentiate from its ancestor *Globanomalina planocompressa* (Berggren and Norris, 1997), may be used to approximate the AP1b/AP1c zonal boundary in the Austral Realm.

Based on the location at 247.55 mbsf of the Chron C29n/r Magnetozone boundary at ODP Hole 690C (Hamilton, 1990) and the sedimentation rate of 6.7 m/m.y. determined in the lower Danian by Quillévéré and others (2002), the LO of *P. inconstans* is estimated at 63.23 Ma in the Austral Realm. This datum is about 0.2 Ma older than that determined at low latitudes, suggesting that *P. inconstans* originated in the Austral Realm during the Danian.

Stott and Kennett (1990) defined Subzone AP1b as the *Subbotina inconstans* Interval Subzone between the LO of *S. inconstans* (i.e., *Praemurica inconstans*, following Olsson and others, 1999) and the initial occurrence of "*Planorotalites imitatus*" (i.e., *Globanomalina imitata*, following Olsson and others, 1999). Subzone AP1b, as defined herein, is not an equivalent of that of Stott and Kennett (1990) since we used the LO of *S. triloculinoides* as a zonal marker to delineate the base of the subzone and since we chose to avoid ambiguities in the recognition of *G. imitata* (see above).

Following Blow (1979), Stott and Kennett (1990), and Berggren and Norris (1997), *Praemurica trinidadensis* is considered as a synonym of *P. inconstans*. *Parasubbotina varianta* and *Eoglobigerina spiralis* first occur in the upper part of this biostratigraphic interval. Other characteristic taxa include *E. edita*, *E. eobulloides*, *Subbotina trivialis*, *Parasubbotina pseudobulloides*, *Praemurica taurica* and *Globoconusa daubjergensis*.

AP1c. *Praemurica inconstans*/*Globoconusa daubjergensis* Concurrent-range Subzone (base same, top different from *Globanomalina compressa*/*Praemurica inconstans*-*Praemurica uncinata* Interval Subzone [P1c] of Berggren and others, 1995; see Figure 5).

Definition: Biostratigraphic interval characterized by the concurrent range of the nominate taxa from the LO of *G. compressa* and/or *P. inconstans* to the HO of *Globoconusa daubjergensis* (Fig. 4).

Magnetostratigraphic calibration: None.

Estimated age: Base 63.23, top 61.20 Ma; early Paleocene (Danian).

Remarks: There was no AP1c Subzone defined in Stott and Kennett's austral zonal scheme. The LO of *Globanomalina compressa* can be used to approximate the AP1b/AP1c zonal boundary (see above). We estimate the LO of *P. inconstans* (and/or the LO of *G. compressa*) at 63.23 Ma (see above). The HO of *Globoconusa daubjergensis* is correlated with an unconformity at ~227.9 mbsf in ODP Hole 690C (Quillévéré and others, 2002). A greater than 2 m.y hiatus (61.7–59.7 Ma) is associated with this unconformity and, as a result, the age of the top of Subzone AP1c cannot be directly calibrated. However, Quillévéré (2000) has shown that the HO of *G. daubjergensis* can be used to delineate or approximate the low-latitude P1/P2 biochronal boundary (61.20 Ma; Berggren and others, 1995, 2000). This is in good agreement with the age estimate of 61.10 Ma for the HO of *G. daubjergensis* at Site 738 (Table 1).

Subbotina triloculinoides, *Parasubbotina pseudobulloides* and *Praemurica inconstans* dominate the planktonic foraminiferal assemblages in this subzone. The LOs of *Chiloguembelina wilcoxensis*, *Eoglobigerina spiralis*, and *Parasubbotina varianta*, and the HO of *Praemurica taurica* occur in the lower part of the subzone. Other characteristic species of this biostratigraphic interval include *E. edita* and *Chiloguembelina midwayensis*.

AP2. *Parasubbotina varianta* Partial-range Zone (herein defined).

Definition: Biostratigraphic interval containing the partial range of the nominate taxon from the HO of *Globoconusa daubjergensis* to the LO of *Acarinina subsphaerica* (Fig. 4).

Magnetostratigraphic calibration: None.

Estimated age: Base 61.20, top 59.20 Ma; early Paleocene (Danian; Fig. 5, Table 2).

Remarks: The age of the base of Zone AP2 is estimated at ~61.20 Ma (see above). We acknowledge that high-latitude records are poor around the Danian/Selandian boundary.

Zone AP2 is marked by the initial occurrence of acarininids and morozovellids. At ODP Hole 750A, Quillévéré and others (2001) found the LO of *A. strabocella* at about 61.0 Ma. This age determi-

nation was based on the presence of numerous specimens that were collected in the same horizons as *Morozovella praeangulata*, which is commonly identified at low latitudes in biozones P2 and lower P3a (Berggren and Norris, 1997; Olsson and others, 1999). The overlapping ranges of *M. praeangulata* and *A. strabocella* and the occurrence of the latter species below the LO of *M. angulata* (marker for the base of Biozone P3a at low latitudes) suggest that ODP Hole 750A contains the oldest record of acarininids presently known from the deep sea, and that these acarininids are at least as old as 61.0 Ma. At ODP Hole 738C, Huber (1991b) described contemporaneous *Acarinina mckannai* and *M. praeangulata*, but we believe that the specimens figured as *A. mckannai* by Huber (1991b) are more confidently attributable to *A. strabocella*. Zone AP2 is not recorded at ODP Hole 690C because of a recovery gap between Cores 12X and 13X. Recent studies (Quillévéré, 2000) do not support Stott and Kennett's (1990) recognition of the LO of *Muricoglobigerina mckannai* (i.e., *A. mckannai*, following Olsson and others, 1999; Fig. 5) at the base of Core 12X. This species appears higher (~3 m) in the core and we believe that Stott and Kennett's interpretation may also result from their misidentification of *A. strabocella* as *A. mckannai*.

The initial appearance of the cosmopolitan species *A. subsphaerica* and *A. nitida* (*A. esnaensis* of Stott and Kennett, 1990) occurred simultaneously by 59.20 Ma throughout the oceans, at low as well as high latitudes (Quillévéré and others, 2001; Quillévéré and Norris, 2003). Therefore, we assign an age of 59.20 Ma to the top of Zone AP2. This is in good agreement with the age estimate of 59.10 Ma for the LO of *A. subsphaerica* at Site 738 (Table 1).

Parasubbotina varianta is very abundant throughout Zone AP2. *Subbotina triloculinoides* and *Parasubbotina pseudobulloides* also dominate the planktonic foraminiferal assemblages in this zone. At both ODP Holes 690C and 750A, the LO of *Subbotina triangularis* occurs close to that of *A. strabocella* and the HO of *Praemurica inconstans*, *Eoglobigerina spiralis* and *E. edita* occur close to the top of Zone AP2. At ODP Hole 750A, the HO of *Morozovella praeangulata* occurs in the lower part of Zone AP2 slightly above the horizon where *M. angulata* and *M. conicotruncana* first appear (Quillévéré, 2000; Quillévéré and others, 2001). At ODP Hole 738C, *M. conicotruncana* (i.e., *Acarinina apantesma* of Huber, 1991b) was identified within Zone AP3. No morozovellids were found in the Paleocene sediments of ODP Sites 689 and 690 (Kennett and Stott, 1990; Quillévéré and others, 2002), except within levels where the CIE is recovered (see below). Other characteristic species of this biostratigraphic interval include *Globanomalina compressa* and *Globanomalina imitata*.

AP3. *Acarinina subsphaerica*/*Subbotina triloculinoides* Concurrent-range Zone (herein defined).

Definition: Biostratigraphic interval characterized by the concurrent range of the nominate taxa from the LO of *Acarinina subsphaerica* to the HO of *Subbotina triloculinoides* (Fig. 4).

Magnetostratigraphic calibration: See above for calibration of the LO of *A. subsphaerica*. The HO of *S. triloculinoides* has not been reliably correlated with the magnetic polarity stratigraphy at ODP Hole 690B (see Ali and others, 2000, for comments on the reliability of magnetostratigraphic zones C25n and C25r of Spiess, 1990).

Estimated age: Base 59.20, top 56.50 Ma; late Paleocene (Selandian and Thanetian; Fig. 5, Table 2).

Remarks: The age of the base of Zone AP3 is estimated at 59.2 Ma (see above). The HO of *S. triloculinoides* is correlated with an unconformity at ~185.7 mbsf in ODP Hole 690B (Quillévéré and others, 2002). A ~600 kyr hiatus (56.5–55.9 Ma) is associated with this unconformity and the age of the top of Zone AP3 cannot be directly calibrated. Because *S. triloculinoides* is a deep-dwelling planktonic foraminifer at low latitudes (e.g., Olsson and others, 1999), we believe it is more parsimonious to arbitrarily assign the same extinction age in high latitudes as is recognized in tropical to subtropical records (i.e., 56.5 Ma at DSDP Site 384; Berggren and others, 2000). The ~1 m.y. discrepancy between this age and the HO of *S. triloculinoides* recorded at ODP Site 738 is attributed to poor core recovery at the latter site.

At ODP Hole 690B, the LOs of *A. subsphaerica* and *A. mckannai* occur in the same sample (Quillévéré, 2000). Because of its long duration (~2.7 m.y.), Zone AP3 is characterized by numerous LOs (*Subbotina velascoensis*, *Parasubbotina aff. varianta*, *Globanomalina pseudomenardii*, *G. chapmani*) and HOs (*P. pseudobulloides*, *P. var-*

ianta, *G. imitata*, *A. strabocella*). Other characteristic elements of this biostratigraphic interval include *S. triangularis* and *A. nitida*.

AP4. *Acarinina mckannai* Partial-range Zone (herein defined).

Definition: Biostratigraphic interval characterized by the partial range of the nominate taxon from the HO of *Subbotina triloculinoides* to the LO of *Globanomalina australiformis* (Fig. 4).

Magnetostratigraphic calibration: The LO of *G. australiformis* is correlated with the early part of Chron C24r (Ali and others, 2000).

Estimated age: Base 56.50, top 55.55 Ma; late Paleocene (Thanetian; Fig. 5, Table 2).

Remarks: The age of the base of Zone AP4 is estimated at 56.50 Ma (see above). At ODP Hole 690B, the LO of *G. australiformis* occurs about 0.5 m below the base of the CIE (Quillévére, 2000). Based on the location of the base of the CIE at ~170.76 mbsf (Bains and others, 1999) and the sedimentation rate of 38.7 m/m.y. determined in the late Thanetian by Quillévére and others (2002), the LO of *G. australiformis* is estimated at 55.55 Ma.

Stott and Kennett (1990) defined Zone AP4 as the *Acarinina praepentacamerata* Interval Zone between the initial occurrence of *A. praepentacamerata* and the first occurrence of *Planorotalites australiformis* (i.e., *Globanomalina australiformis*, following Olsson and others, 1999). The base of Zone AP4 has been redefined herein because of the ambiguous taxonomic significance of *A. praepentacamerata* (see Olsson and others, 1999). We believe that Stott's and Kennett's (1990) interpretation may result from their misidentification of *A. strabocella* and/or *A. mckannai* as *A. praepentacamerata*.

At ODP Hole 690B the HO of *S. triloculinoides* and the LO of *Subbotina patagonica* occur in the same level, but this may be an artifact related to the unconformity at ~185.9 mbsf (see Quillévére and others, 2002). *Acarinina mckannai* ranges throughout Zone AP4, where it is very abundant. This zone is also characterized by the LOs of *Acarinina soldadoensis* and *A. coalingsensis* (i.e., *A. triplex* of Huber, 1991b). At low latitudes, the LO of *A. soldadoensis* is ~56.4 Ma and corresponds to the base of Subzone P4c (Berggren and others, 1995; 2000; Olsson and others, 1999). As was pointed out by Quillévére and others (2001), this species appears considerably later in the circum-Antarctic region than at low latitudes. The fossil assemblages of Zone AP4 also include *Acarinina subsphaerica*, *A. nitida*, *Chiloguembelina wilcoxensis*, *Subbotina velascoensis*, *S. triangularis*, *Parasubbotina* aff. *variata*, and *Globanomalina chapmani*.

ANTARCTIC EOCENE (AE) BIOZONATION

AE1. *Globanomalina australiformis*/*Chiloguembelina wilcoxensis* Concurrent-range Zone (herein defined).

Definition: Biostratigraphic interval characterized by the overlapping ranges of the nominate taxa between the LO of *Globanomalina australiformis* and the HO of *Chiloguembelina wilcoxensis* (Fig. 6).

Magnetostratigraphic calibration: See above for the LO of *G. australiformis*. The HO of *C. wilcoxensis* has not been calibrated.

Estimated age: Base 55.55 Ma, top ~53.10 Ma; latest Paleocene (Thanetian) to early Eocene (Spartan and early Ypresian; Fig. 7, Table 2).

Remarks: The age of the base of Zone AE1 is estimated at 55.55 Ma (see above). At ODP Holes 690B, 738C, 747A, 747B and 748C, *M. subbotinae* and *M. gracilis* appear simultaneously (Kelly, 2002; Huber, 1991b; Berggren, 1992) and slightly above the LO of *G. australiformis*. Both morozovellid species are rare, but consistently present within most of their stratigraphic range, which is very brief at all austral locations. Kelly (2002) showed that the LOs of these taxa occur immediately below the CIE level at ODP Hole 690B (i.e., 170.76 mbsf; Bains and others, 1999). At site 738, the LOs of these taxa were recorded immediately above the CIE together with the LO of *Pseudohastigerina wilcoxensis*. In low latitudes, the LO of *M. subbotinae* is at the top of Chron C25n and the LO of *M. gracilis* occurs a short time later (Berggren and others, 1995). Thus, the occurrence of such morozovellid species in high southern latitudes is part of the extratropical excursion of low-latitude forms associated with the Paleocene-Eocene Thermal Maximum (PETM). Indeed, the high diversity of acarininids and presence of keeled morozovellids within Zone AE1 reflects the expansion of warm surface waters into the circum-Antarctic region during the warming event. Based on the location of the CIE at Hole 690B with a sedimentation rate of 38.7 m/m.y. determined for the late

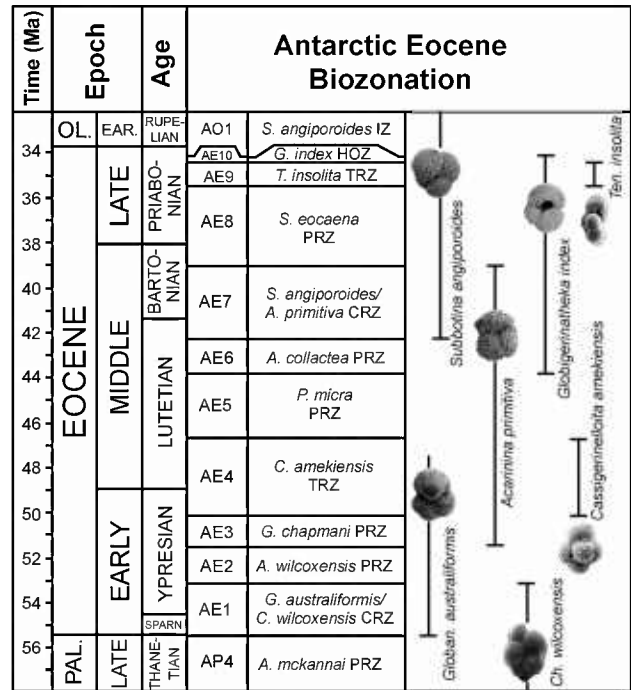


FIGURE 6. Planktonic foraminifer species used to define the new Antarctic Eocene (AE) zones. Stratigraphic ranges are shown with horizontal lines representing zonal datum levels. Time scale based on Berggren and others (1995) with the inclusion of the Spartan Stage as defined by Aubry and others (2003).

Thanetian to early Ypresian interval (Quillévére and others, 2002), the LOs of *M. subbotinae* and *M. gracilis* are estimated at 55.52 Ma. This is in good agreement with the age estimate of 55.39 Ma at Site 738.

Chiloguembelina wilcoxensis is a distinctive element of late Paleocene and earliest Eocene assemblages at austral latitudes, although it has typically been placed in the imprecise category of "larger chiloguembelinids" (e.g., Stott and Kennett, 1990; Nocchi and others, 1991). Following its LO within Zone AP4, this taxon becomes moderately abundant until its extinction at the top of Zone AE1. Other species found within this biostratigraphic interval include *Subbotina triangularis*, *S. velascoensis*, *S. patagonica*, *Parasubbotina* aff. *variata*, and numerous acarininids (*A. nitida*, *A. subsphaerica*, *A. mckannai*, *A. soldadoensis*, and *A. coalingsensis*).

AE2. *Acarinina wilcoxensis* Partial-range Zone (herein defined).

Definition: Biostratigraphic interval containing the partial range of the nominate taxon from the HO of *Chiloguembelina wilcoxensis* to the LO of *Acarinina primitiva* (Fig. 6).

Magnetostratigraphic calibration: The HO of *C. wilcoxensis* has not been calibrated. The LO of *A. primitiva* was correlated with the Chron C22n/C22r boundary at Site 690 (Stott and Kennett, 1990).

Estimated age: Base ~53.10, top ~51.49 Ma; early Eocene (Ypresian; Fig. 7, Table 2).

Remarks: *Acarinina wilcoxensis* (*sensu* Berggren and others, in press) ranges below Zone AE2, with its LO correlating with the upper third of the range of *C. wilcoxensis* and near the base of the range of *G. australiformis* (Huber, 1991b). The top of Zone AE2 may be difficult to identify with certainty because of the gradual morphologic transition from *Acarinina coalingsensis* to *A. primitiva*. *Acarinina primitiva* is distinguished by its triangular (broadly wedge-shaped) final-whorl chambers that increase gradually in size, in contrast to the more rounded, more equidimensional and inflated chambers of *A. coalingsensis* (Berggren and others, in press).

Characteristic species within this zone include *Globanomalina australiformis*, *G. chapmani*, *Subbotina triangularis*, *S. velascoensis*, *S. patagonica*, *Parasubbotina* aff. *variata*, *Acarinina coalingsensis*, *A. interposita*, *A. soldadoensis*, *A. subsphaerica* and *A. wilcoxensis*. *Globanomalina planoconica* has its HO in the upper part of this zone.

EOCENE TIME SCALE

TIME (Ma)	CHRON	POLARITY	EPOCH	AGE	CALCAREOUS NANNOPLANKTON		PLANKTONIC FORAMINIFERA							
					Martini (1971)	Bukry (1973, 1975)	Tropical			Circum-Antarctic				
							Berggren and others (1995)	Berggren and Pearson (2005)		S&K (1990)	Huber (1991)	This Study		
32	C12n		OLIGOCENE	EARLY	RUPELIAN	NP21	CP16	a	P19	O2	<i>T. ampliapertura</i> HOZ	AP13	AO1	<i>S. angiporoides</i> HOZ
33	C12r								P18	O1	<i>P. naguiewichensis</i> HOZ			
34	C13n		LATE	PRIABONIAN	NP19-20	CP15		P16	E16	<i>H. alabamensis</i> HOZ	AP12	AE10	<i>G. index</i> HOZ	
35	C13r							P15	E15	<i>G. index</i> HOZ				
36	C16n							P14	E14	<i>G. seminvolvata</i> HOZ				
37	C17n							P13	E13	"M." <i>crassata</i> HOZ				
38	C18n		MIDDLE	BARTONIAN	NP17	CP14	b	P12	E11	<i>M. lehneri</i> PRZ	AP10	AE7	<i>S. angiporoides</i> / <i>A. primitiva</i> CRZ	
39	C18r							P11	E10	<i>A. topilensis</i> PRZ				
40	C19r		EARLY	YPRESIAN	NP16	CP13	a	P10	E9	<i>G. kugleri</i> / <i>M. aragonensis</i> CRZ	AP9	AE5	<i>P. micra</i> PRZ	
41	C20n							P9	E8	<i>G. nuttalli</i> LOZ				
42	C20r							P8	E7	<i>A. cuneicamerata</i> LOZ				
43	C21n							P7	E5	<i>M. aragonensis</i> / <i>M. subbotinae</i> CRZ				
44	C21r		LUTETIAN	NP15	CP12	c	b	P6b	E4	<i>M. formosa</i> LOZ	AP6a	AE1	<i>Gl. australiformis</i> / <i>C. wilcoxensis</i> CRZ	
45	C22n							P6a	E3	<i>M. marginodentata</i> PRZ				
46	C22r		EARLY	YPRESIAN	NP14	CP11	a	P5	E2	<i>M. subbotinae</i> CRZ	AP5	AE2	<i>A. wilcoxensis</i> PRZ	
47	C23n							P4	E1	<i>M. subbotinae</i> CRZ				
48	C23r		LUTETIAN	NP13	CP10	b	a	P3	E0	<i>M. subbotinae</i> CRZ	AP4	AE3	<i>G. chapmani</i> PRZ	
49	C24n							P2	E0	<i>M. subbotinae</i> CRZ				
50	C24r		LUTETIAN	NP12	CP9	a	b	P1	E0	<i>M. subbotinae</i> CRZ	AP4	AE4	<i>A. mckennai</i> PRZ	
51	C24n							P0	E0	<i>M. subbotinae</i> CRZ				
52	C24r		LUTETIAN	NP11	CP8	a	b	P0	E0	<i>M. subbotinae</i> CRZ	AP4	AE4	<i>A. mckennai</i> PRZ	
53	C24n							P0	E0	<i>M. subbotinae</i> CRZ				
54	C24r		LUTETIAN	NP10	CP8	a	b	P0	E0	<i>M. subbotinae</i> CRZ	AP4	AE4	<i>A. mckennai</i> PRZ	
55	C24n							P0	E0	<i>M. subbotinae</i> CRZ				
56	C24r		LUTETIAN	NP9	CP8	a	b	P0	E0	<i>M. subbotinae</i> CRZ	AP4	AE4	<i>A. mckennai</i> PRZ	
57	C24n							P0	E0	<i>M. subbotinae</i> CRZ				

FIGURE 7. Correlation of Antarctic Eocene biozonation defined in this study with the original Antarctic Paleogene biozonation of Stott and Kennett (1990), the new Eocene tropical planktonic foraminiferal zonation of Berggren and Pearson (2005), and the standard calcareous nannoplankton biostratigraphies of Martini (1971) and Bukry (1973, 1975) using the Berggren and others (1995) time scale with the inclusion of the Sparnacian Stage as defined by Aubry and others (2003).

AE3. *Globanomalina chapmani* Partial Range Zone (herein defined).

Definition: Biostratigraphic interval containing the partial range of nominate taxon from the LO of *Acarinina primitiva* to the LO of *Cassigerinelloita amekiensis* (Fig. 6).

Magnetostratigraphic calibration: See above for calibration of the LO of *A. primitiva*. The LO of *C. amekiensis* has not been calibrated.

Estimated age: Base ~51.49, top ~50.23 Ma; late early Eocene (Ypresian; Fig. 7, Table 2).

Remarks: See remarks above for criteria used to identify the LO of *A. primitiva*. Recognition of the LO of *C. amekiensis* requires a search in the finer sieved residue fractions because of the small size of this species. Characteristic species of this zone include *G. chapmani*, which ranges throughout the zone in low to moderate abundance, and *Subbotina patagonica*, *A. pentacamerata*, *A. wilcoxensis*, and *G. australiformis*.

AE4. *Cassigerinelloita amekiensis* Taxon-range Zone (herein defined).

Definition: Total range of the nominate taxon (Fig. 6).

Magnetostratigraphic calibration: None.

Estimated age: Base ~50.23 Ma, top ~46.70 Ma. Early middle Eocene (late Ypresian-early Lutetian; Fig. 7, Table 2).

Remarks: Although Stolk (1965) considered *C. amekiensis* as a useful biomarker in upper lower to lower middle Eocene sediments in Nigeria, this species has been overlooked in most low latitude studies,

probably because of its small size and relatively low abundance. It is a distinctive and consistently occurring component of lower middle Eocene assemblages from southern high latitudes (Li and Radford, 1992). The extinction of *C. amekiensis* (= "*Globigerina*" sp. B of Stott and Kennett, 1990) has been recorded within several meters below the HO of *G. australiformis* at all southern high-latitude sites (Nocchi and others, 1991; Huber, 1991b; Li and others, 1992; H. Coxall, communication, 2004).

Characteristic elements of this zone include *Globanomalina chapmani*, *Acarinina bullbrookii*, *A. primitiva*, *Subbotina linaperta* (middle to upper part), and *S. patagonica*. The LO of *Jenkinsina triseriata* occurs at or near the base and the HO of *G. australiformis* occurs at or near the top of Zone AE4.

AE5. *Pseudohastigerina micra* Partial-range Zone (herein defined).

Definition: Biostratigraphic interval containing the partial range of nominate taxon from the HO of *Cassigerinelloita amekiensis* to the LO of *Globigerinatheka index* (Fig. 6).

Magnetostratigraphic calibration: The HO of *C. amekiensis* has not been paleomagnetically calibrated, but is estimated at 46.70 Ma based on the Site 738 age model (Fig. 3). The LO of *G. index* was correlated with the Chron C20n/C20r boundary at ODP Site 689 by Stott and Kennett (1990), which corresponds with 43.70 Ma according to the time scale of Berggren and others (1995). The 42.9 Ma calibrated age reported for the FAD of *G. index* in Berggren and others (1995, Table 9) was erroneous (Berggren, written communication, 2004). In the Um-

brian Marche Basin (Napoleone and others, 1983) and at ODP Sites 1209 and 1211 on Shatsky Rise (Petrizzo, 2004) the LO of *G. index* was recorded just below the extinction of *Morozovella aragonensis* (i.e., within upper Zone E9 and below the Chron C20n/C20r boundary). These reports are consistent with the 44.08 Ma age estimate obtained for the LO of *G. index* using the age-depth profile for Site 738.

Estimated age: Base ~46.70, top 43.70 Ma; middle Eocene (middle Lutetian; Fig. 7, Table 2).

Remarks: The base of Stott and Kennett's (1990) *P. micra* Zone (AP9) was defined by the LO of *P. micra*, which was reported to immediately follow the *Acarinina bullbrooki* Zone (AP8) whose base was defined on the LO of *A. bullbrooki*. Because the LO of *P. micra* was identified below the LO of *A. bullbrooki* at Site 738, Huber (1991b) redefined the base of AP9 using the LO of *A. matthewsae* and designated this interval as the *Acarinina matthewsae* Zone. However, consistent identification of the *A. matthewsae* Zone is difficult given the close morphologic similarity between the nominate taxon and *A. bullbrooki*, which are considered by some authors (e.g., Pearson and others, in press) as synonymous. Thus, the *A. matthewsae* datum of Huber (1991b) has been abandoned.

Pseudohastigerina micra is consistently present in low to moderate abundance throughout this zone. It co-occurs with *Acarinina bullbrooki* (*sensu* Berggren and others, in press), *A. primitiva*, *Subbotina linaperta* and *S. patagonica*.

AE6. *Acarinina collectea* Partial-range Zone (herein defined; base the same but top different from *Acarinina collectea* Partial Range Zone [AP10] of Stott and Kennett, 1990).

Definition: Biostratigraphic interval containing the nominate taxon from the LO of *Globigerinatheka index* to the LO of *Subbotina angiporoides* (Fig. 6).

Magnetostratigraphic calibration: See discussion above for the LO of *G. index*. The LO of *S. angiporoides* has not been paleomagnetically calibrated.

Estimated age: Base 43.70 Ma, top ~42.33 Ma; middle Eocene (late Lutetian; Fig. 7, Table 2).

Remarks: Zone AE6 differs from Stott and Kennett's (1990) *A. collectea* Zone (AP10) by using the LO of *S. angiporoides* rather than the HO of *A. primitiva* to define its top. Although the lowest occurrence of *G. index* was recorded above that of *S. angiporoides* at Maud Rise and Site 748 (Stott and Kennett, 1990; Berggren, 1992), the reverse was observed at Sites 703, 738 and 1135 (Nocchi and others, 1991; Huber, 1991b; Coffin and others, 2000). After careful study of species distributions at Sites 738 and 690 and strict application of species concepts discussed in Pearson and others (in press), we conclude that the lowest occurrence of *G. index* is below that of *S. angiporoides* by at least 20 m of section at both sites.

Characteristic taxa found within Zone AE6 include *Acarinina collectea* (including subangular variants designated as *A. cf. collectea* in Huber, 1991b; Berggren and others, in press), which consistently occurs in low to moderate abundance throughout the zone, *A. bullbrooki*, *A. primitiva*, *Globorotaloides eovariabilis* (= *Globorotaloides* aff. *testarugosa* of Huber, 1991b), *G. quadrocamerata* (= *Globorotaloides suteri* of Huber, 1991b) and *Chiloguembelina ototara*. In the lower part of this zone at Kerguelen Plateau sites 738 and 748, *Morozovella spinulosa* comprises a distinctive component of the assemblages. However, *M. spinulosa* has not been reported in the South Atlantic sector of the Southern Ocean.

AE7. *Subbotina angiporoides*/*Acarinina primitiva* Concurrent-range Zone (herein defined).

Definition: Biostratigraphic interval characterized by the concurrent range of the nominate taxa from the LO of *Subbotina angiporoides* to the HO of *Acarinina primitiva* (Fig. 6).

Magnetostratigraphic calibration: The LO of *S. angiporoides* has not been calibrated. The HO of *A. primitiva* was correlated with middle Chron C18n at ODP Sites 689 and 690 (Stott and Kennett, 1990) and calibrated as 39.00 Ma (Berggren and others, 1995).

Estimated age: Base ~42.33, top 39.00 Ma; late middle Eocene (late Lutetian-early Bartonian) (Fig. 7, Table 2).

Remarks: The LO of *S. angiporoides* (*sensu* Olsson and others, in press) has been recorded above the LO of *G. index* at southern Indian Ocean sites 738 and 1137 (Huber, 1991b; Coffin and others, 2000),

and southern South Atlantic sites 690 and 703 (Stott and Kennett, 1990; Nocchi and others, 1991). Using the age model for Site 738 we estimate that these two datum events are separated by at least 1.5 m.y. The extinction of *A. primitiva* is an easily recognizable datum that precedes the extinctions of *A. collectea* and *Subbotina linaperta*. The age estimate for the LAD of *A. primitiva* is 39.06 Ma, which is in very good agreement with the calibrated age of 39.00 Ma reported by Berggren and others (1995).

Characteristic species within the zone include *S. angiporoides*, which is relatively rare, *P. micra*, *S. linaperta*, *G. index*, *G. eovariabilis*, *G. quadrocamerata*, *C. ototara* and *A. collectea*. The mid-Eocene Thermal Maximum event (MECO), which was identified at 92.85 mbsf at Site 738 by Bohaty and Zachos (2003), occurs within the lower part of this zone (Table 1).

AE8. *Subbotina eocaena* Partial-range Zone (herein defined).

Definition: Biostratigraphic interval containing the partial range of the nominate taxon from the HO of *Acarinina primitiva* to the LO of *Tenuitella insolita* (Fig. 6).

Magnetostratigraphic calibration: See above for calibration of *A. primitiva*. The LO of *T. insolita* has not been paleomagnetically calibrated.

Estimated age: Base 39.00-, top ~35.50 Ma; late middle to early late Eocene (late Bartonian-early Priabonian; Fig. 7, Table 2).

Remarks: Zone AE8 comprises Zone AP11 and lower Zone AP12 of the Stott and Kennett (1990) zonal scheme. The extinction of *S. linaperta*, which was used to define the Zone AP11/AP12 boundary in Stott and Kennett's biozonation, may be difficult to identify because of stratigraphic overlap of "*sensu stricto*" forms (bearing a large final chamber that is compressed in the direction of coiling) and "*sensu lato*" forms (morphologically intermediate between *S. linaperta* s.s. and *S. utilisindex*; see Huber, 1991b, Berggren, 1992). At Site 738 *S. linaperta* s.s. last occurs at the level of a hiatus spanning from ~36.8 to 39.2 Ma (Fig. 2). Because of uncertainty regarding accurate determination of the HO of *S. linaperta*, we have abandoned recognition of this bioevent. The LO of *T. insolita* is a useful biomarker for delineating the top of Zone AE8 because of its distinctive morphologic features (e.g., areal aperture and micropore wall texture).

Subbotina eocaena, which first occurs in the lower middle Eocene and ranges into the lowermost Oligocene, occurs in rare abundance but consistently throughout Zone AE8. The last remaining quadrate acarinid, *A. medizai*, becomes extinct in the middle of this zone. Characteristic species include *S. angiporoides*, *G. index*, *G. eovariabilis*, *G. quadrocamerata*, *P. micra* and *C. ototara*. *Paragloborotalia nana*, *P. pseudocontinua*, *S. linaperta* and *A. echinata* have their lowest occurrences in the middle to upper part of this zone.

AE9. *Tenuitella insolita* Taxon-range Zone (= *Globorotalia insolita* Zone of Jenkins and Orr 1972 and *Praetenuitella insolita* Zone of Li and others [1992]).

Definition: Biostratigraphic interval characterized by the total range of the nominate taxon (Fig. 6).

Magnetostratigraphic calibration: None.

Estimated age: Base ~35.50 Ma, top ~34.40 Ma; late Eocene (late Priabonian) (Fig. 7, Table 2).

Remarks: *Tenuitella insolita* is easily distinguished from other micropore species by the presence of a highly arched, narrow aperture (Huber and others, in press). At all of the austral sites the LO of *insolita* occurs just above the HOs of *Subbotina linaperta* and *Acarinina medizai* and the HO occurs just below the HO of *Globigerinatheka index*.

Characteristic species of this zone include *S. angiporoides*, *G. index*, *G. quadrocamerata*, *G. eovariabilis*, *Chiloguembelina ototara*, *Catapsydrax echinatus*, and *C. unicavus*. *Subbotina utilisindex* has its lowest occurrence in the lower part of this zone, *Paragloborotalia nana* and *P. pseudocontinua* have their lowest occurrences in the middle of the zone, and *Pseudohastigerina micra* last occurs in the upper part of the zone.

AE10. *Globigerinatheka index* Highest-occurrence Zone (herein defined; different from *G. index* Zone of Jenkins [1966], *G. index* Partial Range Zone of Stott and Kennett [1990]; top same but base different from the *G. index* Interval Zone [E15] of Berggren and Pearson, 2005; see Fig. 7).

Definition: Biostratigraphic interval from the HO of *Tenuitella insolita* to the HO of the nominate taxon (Fig. 6).

Magnetostratigraphic calibration: The HO of *T. insolita* has not been paleomagnetically calibrated. The HO of *G. index* was recorded in Chron C13r in the Umbrian Apennines (Berggren and others, 1995) and the Agulhas Ridge in the Southern Ocean (Galeotti and others, 2002). On Kerguelen Plateau Roberts and others (2003) correlated this datum with Chron C13r at Site 748 and Chron C15r at Site 744 (see above). Although Stott and Kennett (1990) correlated the LAD of *G. index* with the top of Chron C16n at Maud Rise Site 689, Spiess (1990) presented an alternative interpretation of the magnetic stratigraphy that suggested assignment to Chron C15n, which significantly reduces this temporal discrepancy. We prefer to use the most consistently observed Chron C13r correlation for this datum with an assigned age of 34.30 Ma (Berggren and others, 1995). This is in good agreement with the 34.28 Ma age estimate obtained from the Site 738 age-depth model (Table 1).

Estimated age: Base ~34.49 Ma, top 34.30 Ma; late Eocene (late Priabonian; Fig. 7, Table 2).

Remarks: Zone AE10 is the youngest zone used to subdivide austral Eocene sequences. It is much younger than Stott and Kennett's (1990) middle *G. index* Zone (AP11), which was defined using the HO of *Acarinina primitiva* for the base and the LO of *S. linaperta* for the top. Jenkins's (1966) *G. index* Zone was also used for the middle Eocene, with its base and top defined using the LO of *G. index* and the LO of *Chiloguembelina cubensis*, respectively.

The extinction of *G. index* is used to approximate the position of the Eocene/Oligocene boundary in austral latitudes, as the turborotaliids and hantkeninids, which are used to more precisely delineate the boundary at low latitudes, are absent from southern, high-latitude sites. Comparison of age estimates for the HO of *index* at Site 738 (Table 1; Roberts and others, 2003) with the age calibration of Berggren and others (1995) for low latitudes shows good agreement, suggesting that the extinction of this species was essentially synchronous.

Species typically found in Zone AE10 include *Chiloguembelina cubensis*, *S. angiporoides*, *S. utilisindex*, *Catapsydrax dissimilis*, *Globorotaloides* spp., and the microporifera species *Tenuitella patefacta* and *T. praegemma*. *Tenuitella gemma* and *T. munda* first occur at the top of or just above Zone AE10.

ANTARCTIC OLIGOCENE (AO) BIOZONATION

AO1. *Subbotina angiporoides* Highest-occurrence Zone (= *S. angiporoides* Interval Zone [AP13] of Stott and Kennett, 1990; base different top same as *Globigerina angiporoides* Zone of Jenkins, 1966).

Definition: Biostratigraphic interval from the HO of *G. index* to the HO of *S. angiporoides* (Fig. 8).

Magnetostratigraphic calibration: See above for the HO of *G. index*. The HO of *S. angiporoides* was recorded in Chron C11n at sites 689B and 690B and assigned an age of 30.00 Ma (Berggren and others, 1995).

Estimated age: Base 34.30, top 30.00 Ma; latest Eocene to early Oligocene (late Priabonian-Rupelian).

Remarks: Zone AO1 differs from the *Globigerina angiporoides* Zone of Jenkins (1966) in that Jenkins used the HO of *Globigerina brevis* to define the top of his zone. Austral assemblages in Zone AO1 are characteristically low in diversity and dominated by *C. cubensis*, *S. angiporoides*, *Catapsydrax unicavus*, and *C. dissimilis*. Also occurring in this zone are *Paragloborotalia nana*, *Subbotina brevis*, and several species of *Tenuitella*, including *T. patefacta*, *T. praegemma*, *T. gemma* and *T. munda*. The LOs of *Globigerina labiacrassata* and *Globigerina euapertura* occur in the lower to middle Zone AO1 and the HO of *S. utilisindex* occurs in upper Zone AO1.

AO2. *Chiloguembelina cubensis* Highest-occurrence Zone (= *C. cubensis* Interval Subzone [AP14a] of Stott and Kennett, 1990; Zone AP14 of Berggren, 1992).

Definition: Biostratigraphic interval from the HO of *Subbotina angiporoides* to the Highest Common Occurrence (HCO) of the nominate taxon (Fig. 8).

Magnetostratigraphic calibration: See above for HO of *S. angiporoides*. The HCO of *C. cubensis* was correlated with middle Chron C10n and assigned an age of 28.5 Ma (Berggren and others, 1995).

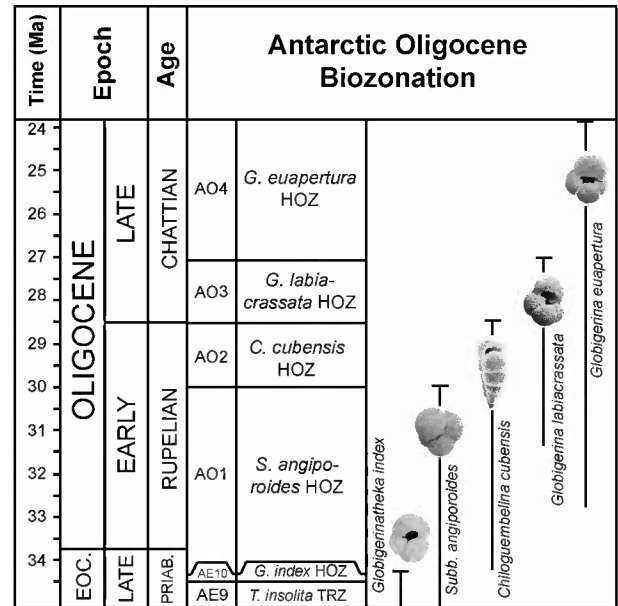


FIGURE 8. Planktonic foraminifer species used to define the new Antarctic Oligocene (AO) zones. Stratigraphic ranges are shown with horizontal lines representing zonal datum levels. Time scale based on Berggren and others (1995) with the inclusion of the Sparnacian Stage as defined by Aubry and others (2003).

Estimated age: Base 30.00 Ma, top 28.50 Ma; late early Oligocene (late Rupelian; Fig. 9, Table 2).

Remarks: The HCO of *C. cubensis* is preferred as the defining datum over the HO of this species because of records of discontinuous, rare occurrences that range into the Miocene. Typical species found within this zone include *C. dissimilis*, *G. euapertura*, *G. praebuloides*, *G. eovariabilis*, and several species of *Tenuitella* (e.g., *T. gemma*, *T. munda*, *T. angustumbilicata*).

AO3. *Globigerina labiacrassata* Highest-occurrence Zone (= *G. labiacrassata* Interval Subzone [AP14b] of Stott and Kennett, 1990, and *G. labiacrassata* Interval Zone of Berggren, 1992).

Definition: Biostratigraphic interval from the HCO of *Chiloguembelina cubensis* to the HO of the nominate taxon.

Magnetostratigraphic calibration: See above for the HCO of *C. cubensis*. The HO of *G. labiacrassata* was recorded in Chron C9n and assigned an age of 27.10 Ma (Berggren and others, 1995).

Estimated age: Base 28.50 Ma, top 27.10 Ma; early late Oligocene (early Chattian).

Remarks: The HO of *G. labiacrassata* was recorded near the top of Chron C9n in Holes 747A and 748B on Kerguelen Plateau (Berggren, 1992) and Holes 689B and 690B on Maud Rise (Stott and Kennett, 1990). Berggren and others (1995) calibrated this datum as 27.1 Ma, the same age assigned to the LAD of *Paragloborotalia opima* and the datum used to define the top of tropical Zone (O5). *Paragloborotalia opima* has not been observed at high austral latitudes.

Characteristic species in this zone include *Globigerina euapertura*, *Globorotalia brazieri*, *C. dissimilis*, *Globorotaloides* spp., *Globigerinita juvenilis*, and several species of *Tenuitella* (e.g., *T. gemma*, *T. munda*, *T. angustumbilicata*).

AO4. *Globigerina euapertura* Highest-occurrence Zone (= AP16 of Berggren, 1992; base and top different from *Globigerina euapertura* Zone of Jenkins, 1966).

Definition: Biostratigraphic interval from the HO of *Globigerina labiacrassata* to the HO of the nominate taxon (Fig. 8).

Magnetostratigraphic calibration: See above for the HO of *G. labiacrassata*. The HO of *G. euapertura* was recorded in Chron C6Cn.2n and assigned an age of 23.8 Ma (Berggren and others, 1995).

Estimated age: Base 27.10 Ma, top 23.80 Ma; late Oligocene (Chattian; Fig. 9, Table 2).

Remarks: Zone AO4 differs from the *Globigerina euapertura* Zone

OLIGOCENE TIME SCALE

TIME (Ma)	CHRONS	POLARITY	EPOCH	AGE	CALCAREOUS NANNOPLANKTON		PLANKTONIC FORAMINIFERA																							
					Martini (1971)	Bukry (1973, 1975)	Tropical		Circum-Antarctic																					
							Berggren and others (1995)	Berggren and Pearson (2005)	S & K (1991)	This study																				
23	C6Bn		MIOCENE	EARLY AQUITANIAN	NN2	CN1	M1b	not studied		not studied	AN1	<i>G. brazieri</i> PRZ																		
24	C6Cn				NN1		M1a	O6	<i>G. ciperensis</i> PRZ		AO4	<i>G. euapertura</i> IZ																		
25	C6Cr		LATE CHATTIAN	NP25	CP19	b	P22			O5			<i>P. opima</i> HOZ	AP14	b	AO3	<i>G. labiacrassata</i> IZ													
26	C7n1							NP24	a		P21	a						O4	<i>G. angulicostata</i> / <i>C. cubensis</i> CRZ	a	AO2	<i>C. cubensis</i> IZ								
27	C7r																						NP23	CP18	P19	O2	<i>T. ampliapertura</i> HOZ	AP13	AO1	<i>S. angiporoides</i> IZ
28	C8n																													
29	C8r		NP21	CP16	P17	E16	<i>H. alabamensis</i> HOZ	AP12	AE10	<i>G. index</i> IZ																				
30	C9n										NP19-20	CP15	P16	E15	<i>G. index</i> HOZ	AE9	<i>T. insolita</i> TRZ													
31	C9r		NP18	P15	E14	<i>G. semirivolata</i> HOZ	AE8	<i>S. linaperta</i> PRZ																						
32	C10n								NP17	CP14	P14	E13	<i>G. index</i> HOZ	AE7	<i>S. linaperta</i> PRZ															
33	C10r		NP16	CP13	P13	E12	<i>G. index</i> HOZ	AE6								<i>S. linaperta</i> PRZ														
34	C11n								NP15	CP12	P12	E11	<i>G. index</i> HOZ	AE5	<i>S. linaperta</i> PRZ															
35	C11r		NP14	CP11	P11	E10	<i>G. index</i> HOZ	AE4								<i>S. linaperta</i> PRZ														
36	C12n								NP13	CP10	P10	E9	<i>G. index</i> HOZ	AE3	<i>S. linaperta</i> PRZ															
37	C12r		NP12	CP9	P9	E8	<i>G. index</i> HOZ	AE2								<i>S. linaperta</i> PRZ														
	C13n								NP11	CP8	P8	E7	<i>G. index</i> HOZ	AE1	<i>S. linaperta</i> PRZ															
	C13r		NP10	CP7	P7	E6	<i>G. index</i> HOZ	AE0								<i>S. linaperta</i> PRZ														
	C14n								NP9	CP6	P6	E5	<i>G. index</i> HOZ	AE-1	<i>S. linaperta</i> PRZ															
	C14r		NP8	CP5	P5	E4	<i>G. index</i> HOZ	AE-2								<i>S. linaperta</i> PRZ														
	C15n								NP7	CP4	P4	E3	<i>G. index</i> HOZ	AE-3	<i>S. linaperta</i> PRZ															
	C15r		NP6	CP3	P3	E2	<i>G. index</i> HOZ	AE-4								<i>S. linaperta</i> PRZ														
	C16n								NP5	CP2	P2	E1	<i>G. index</i> HOZ	AE-5	<i>S. linaperta</i> PRZ															
	C16r		NP4	CP1	P1	E0	<i>G. index</i> HOZ	AE-6								<i>S. linaperta</i> PRZ														
	C17n 1n								NP3	CP0	P0	E-1	<i>G. index</i> HOZ	AE-7	<i>S. linaperta</i> PRZ															

FIGURE 9. Correlation of Antarctic Oligocene biozonation defined in this study with the original Antarctic Paleogene biozonation of Stott and Kennett (1990), the revised tropical planktonic foraminiferal zonation of Berggren and Pearson (2005), and the standard calcareous nannoplankton biostratigraphies of Martini (1971) and Bukry (1973, 1975) using the Berggren and others (1995) time scale with the inclusion of the Sparnacian Stage as defined by Aubry and others (2003).

of Jenkins (1966), which used the HO of *S. angiporoides* to define the base and the LO of *Globoquadrina dehiscens* to define the top.

The LAD of *G. euapertura* was recorded near the top of Chron C6Cn at Hole 748B and near the base of this magnetochron at Holes 747A and 747B, and calibrated at 23.8 Ma (Berggren, 1992). The LOs of *Globoquadrina woodi* and *G. connecta* occur near the base, and the LO of *Turborotalita quinqueloba* is in the middle of this zone. Other characteristic species of this zone include *C. dissimilis*, *Globoquadrina* spp., *Globigerinita juvenilis*, *Turborotalita angustumbilicata*, and *T. clemenciae*.

CONCLUSIONS

The new Antarctic Paleogene biozonation presented in this study provides a more reliable means of correlating marine sequences throughout the circum-Antarctic region than previous zonal schemes, as it is based on recently updated taxonomic concepts and cumulative observations from over 14 ODP drilling sites in the region of the Southern Ocean. This new zonation recognizes five zones and three subzones in the Antarctic Paleocene (AP) scheme, ten zones in the

Antarctic Eocene (AE) scheme, and four zones in the Antarctic Oligocene (AO) scheme.

Because most of the planktonic foraminifer zonal datum markers used in the Antarctic zonation are different from those used to subdivide tropical and subtropical sequences, cross-latitude correlation is best achieved by the generation of age-depth curves constructed from the best bio-, chemo- and magnetostratigraphic data available. Despite the absence of magnetic polarity data, the Paleocene-early Oligocene age model developed herein for ODP Site 738 is well constrained because of the inclusion of unambiguous tie points, such as the Cretaceous/Paleogene boundary and the Paleocene/Eocene boundary CIE, and a number of foraminifer and nannofossil events that have been reliably calibrated elsewhere. This provides the basis for estimating ages for a number of additional foraminifer and nannofossil first and last occurrences, which are probably accurate to within 0.5 m.y. Integrated magnetobiostratigraphic age-depth curves need to be developed for the other circum-Antarctic Paleo-

gene sequences in order to test the reliability of the datum ages estimated from the Site 738 sequence.

ACKNOWLEDGMENTS

Thanks are extended to members of the Paleogene Planktonic Foraminiferal Working Group for their ongoing collaboration and dedication to revising the taxonomy and biostratigraphy of Paleogene planktonic foraminifera. We also thank Bill Berggren and Helen Coxall for discussions regarding planktonic foraminifer biostratigraphy on Kerguelen Plateau, and Bill Berggren for his numerous helpful suggestions and editorial comments on early drafts of the manuscript. This paper benefited further from critical reviews and insightful suggestions by Robert Fleisher, Helen Coxall, Peter McLaughlin, and Brian McGowran. We acknowledge the Ocean Drilling Program and DSDP/ODP Micropaleontologic Reference Centers for providing samples analyzed in this study.

REFERENCES

- ALI, J. R., KENT, D. V., and HAILWOOD, E. A., 2000, Magnetostratigraphic reinvestigation of the Palaeocene/Eocene boundary interval in Hole 690B, Maud Rise, Antarctica: *Geophysical Journal International*, v. 141, p. 639–646.
- ARNEY, J. E., and WISE, S. W., Jr., 2003, Paleocene-Eocene nanofossil biostratigraphy of ODP Leg 183, Kerguelen Plateau, in Coffin, M. F., Frey, F. A., Wallace, P. J., and others, *Proceedings of the Ocean Drilling Program, Scientific Results*, v. 183, p. 1–59 [Online] available from World Wide Web: <http://www-odp.tamu.edu/publications/183.SR-014.htm>.
- AUBRY, M.-P., 1992, Paleogene calcareous nanofossils from the Kerguelen Plateau, Leg 120, in Wise, S. W., Jr., Schlich, R., and others, *Proceedings of the Ocean Drilling Program, Scientific Results, Ocean Drilling Program, College Station, Texas*, v. 120, p. 471–491.
- , 1995, From chronology to stratigraphy: interpreting the lower and middle Eocene stratigraphic record in the Atlantic Ocean, in Berggren, W. A., Kent, D. V., Aubry, M.-P., and Hardenbol, J. (eds.), *Geochronology, Time Scales and Global Stratigraphic Correlations: SEPM (Society for Sedimentary Geology) Special Publication*, no. 54, p. 213–274.
- , BERGGREN, W. A., STOTT, L. D., and SINHA, A., 1996, The upper Paleocene-lower Eocene stratigraphic record and the Paleocene-Eocene boundary carbon isotope excursion: Implications for geochronology, in Knox, R. W., Corfield, R. M. and Dunay, R. E. (eds.), *Correlation of the Early Paleogene in Northwest Europe: Geological Society Special Publication*, no. 101, p. 353–380.
- AUBRY, M.-P., BERGGREN, W. A., VAN COUVERING, J. A., ALI, J., BRINKHUIS, H., CRAMER, B., KENT, D. V., SWISHER, I. C. C., GINGERICH, P. R., HEILMANN-CLAUSEN, C., KNOX, R. W. O., LAGA, P., STEURBAUT, E., STOTT, L. D., and THIRY, M., 2003, Chronostratigraphic Terminology at the Paleocene/Eocene Boundary, in Wing, S. L., Gingerich, P. D., Schmitz, B., and Thomas, E. (eds.), *Causes and Consequences of Globally Warm Climates in the Early Paleogene: Geological Society of America Special Paper*, no. 369, p. 551–566.
- BACKMAN, J., 1986, Late Paleocene to middle Eocene calcareous nanofossil biochronology from the Shatsky Rise, Walvis Ridge and Italy: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 57, p. 43–59.
- BAINS, S., CORFIELD, R. M., and NORRIS, R. D., 1999, Mechanisms of climate warming at the end of the Paleocene: *Science*, v. 285, p. 724–727.
- BARKER, P. F., KENNETT, J. P., and others, 1988, *Proceedings of the Ocean Drilling Program, Initial Reports, Ocean Drilling Program, College Station, Texas*, v. 113, 785 p.
- BARRON, J. A., LARSEN, B., and others, 1989, *Proceedings of the Ocean Drilling Program, Initial Reports, Ocean Drilling Program, College Station, Texas*, v. 119, 942 p.
- BERGGREN, W. A., 1992, Paleogene planktonic foraminifer magnetostratigraphy of the southern Kerguelen Plateau (sites 747–749), in Wise, S. W., Jr., Schlich, R., and others, *Proceedings of the Ocean Drilling Program, Scientific Results: Ocean Drilling Program, College Station, Texas*, v. 120, p. 551–568.
- , AUBRY, M.-P., VAN FOSSEN, M., KENT, D. V., NORRIS, R. D., and QUILLÉVÉRÉ, F., 2000, Integrated Paleocene calcareous plankton magnetobiochronology and stable isotope stratigraphy: DSDP Site 384 (NW Atlantic Ocean): *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 159, p. 1–51.
- , KENT, D. V., SWISHER, I. C. C., and AUBRY, M.-P., 1995, A revised Cenozoic geochronology and chronostratigraphy, in Berggren, W. A., Kent, D. V., Aubry, M.-P., and Hardenbol, J. (eds.), *Geochronology, Time Scales and Global Stratigraphic Correlations: Society of Economic Paleontologists and Mineralogist Special Publication*, no. 54, v. 129–212.
- , and NORRIS, R. D., 1997, Biostratigraphy, phylogeny and systematics of Paleocene trochospiral planktonic foraminifera: *Micropaleontology, Supplement 1*, v. 43, p. 1–116.
- , and PEARSON, P. N., 2005, A revised tropical to subtropical Paleogene planktonic foraminiferal zonation: *Journal of Foraminiferal Research* v. 35, p. xx–yy.
- , PEARSON, P. N., and HUBER, B. T., 2005, Taxonomy, biostratigraphy and phylogeny of Eocene *Acarinina*, in Pearson, P. N., Olsson, R. K., Huber, B. T., Berggren, W. A., and Hemleben, C. (eds.), *Atlas of Eocene Planktonic Foraminifera: Cushman Foundation for Foraminiferal Research, Special Publication*, no. 41, in press.
- BLOW, W. H., 1979, *The Cainozoic Globigerinida*, E. J. Brill, Leiden, v. 1–3, 1413 p.
- BOHATY, S. M., and ZACHOS, J. C., 2003, Significant Southern Ocean warming event in the late middle Eocene: *Geology*, v. 31, p. 1017–1020.
- BUKRY, D., 1973, Low-latitude coccolith biostratigraphic zonation, in Edgar, N. T., Saunders, J. B., and others, *Initial Reports of the Deep Sea Drilling Project: U.S. Government Printing Office, Washington, D.C.*, v. 15, p. 127–149.
- , 1975, Coccolith and silicoflagellate stratigraphy, northwestern Pacific Ocean, Deep Sea Drilling Project Leg 32, in Larson, R. L., Moberly, R., and others, *Initial Reports of the Deep Sea Drilling Project: U.S. Government Printing Office, Washington, D.C.*, v. 32, p. 677–701.
- CIESIELSKI, P. F., KRISTOFFERSEN, Y., and others, 1988, *Proceedings of the Ocean Drilling Program, Initial Reports, Ocean Drilling Program: College Station, Texas*, v. 114, 815 p.
- CLEMENT, B. M., and HAILWOOD, E. A., 1991, Magnetostratigraphy of sediments from Sites 701 and 702, in Ciesielski, P. F., Kristoffersen, Y., and others, *Proceedings of the Ocean Drilling Program, Scientific Results: College Station, Texas, Ocean Drilling Program, vol. 114*, p. 359–366.
- COFFIN, M. F., FREY, F. A., WALLACE, P. J. and others, 2000, *Proceedings of the Ocean Drilling Program, Initial Reports: Ocean Drilling Program, College Station, Texas*, v. 183, p. [Online] available from World Wide Web: http://www-odp.tamu.edu/publications/183_IR/183ir.htm.
- FLORINDO, F., and ROBERTS, A. P., 2005, Eocene-Oligocene magnetobiochronology of ODP Sites 689 and 690, Maud Rise, Weddell Sea, Antarctica: *Geological Society of America Bulletin*, v. 117, p. 46–66.
- GALEOTTI, S., COCCIONI, R., and GERSONDE, R., 2002, Middle Eocene-early Pliocene subantarctic planktic foraminiferal biostratigraphy of Site 1090, Agulhas Ridge: *Marine Micropaleontology*, v. 45, p. 357–381.
- HAILWOOD, E. A., and CLEMENT, B. M., 1991, Magnetostratigraphy of Sites 699 and 700, East Georgia Basin, in Ciesielski, P. F., Kristoffersen, Y., and others, *Proceedings of the Ocean Drilling Program, Scientific Results: College Station, Texas, Ocean Drilling Program v. 114*, pp. 337–353.
- HAMILTON, N., 1990, Mesozoic magnetostratigraphy of Maud Rise, Antarctica, in Barker, P. F., Kennett, J. P., and others, *Proceedings of the Ocean Drilling Program, Scientific Results: Ocean Drilling Program, College Station, Texas*, v. 113, p. 255–260.
- HUBER, B. T., 1991a, Maestrichtian planktonic foraminifer biostratigraphy and the Cretaceous/Tertiary boundary at ODP Hole 738C

- (Kerguelen Plateau, southern Indian Ocean), in Barron, J., Larsen, B., and others, Proceedings of the Ocean Drilling Program, Scientific Results: Ocean Drilling Program, College Station, Texas, v. 119, p. 451–465.
- , 1991b, Paleogene and early Neogene planktonic foraminifer biostratigraphy of ODP Leg 119 Sites 738 and 744, Kerguelen Plateau (southern Indian Ocean), in Barron, J., Larsen, B. and others, Proceedings of the Ocean Drilling Program, Scientific Results: Ocean Drilling Program, College Station, Texas, p. 427–449.
- , OLSSON, R. K., and PEARSON, P. N., 2005, Taxonomy of Eocene Microperforate Planktonic Foraminifera (*Jenkinsina*, *Cassigerinelloita*, *Chiloguembelina*, *Zeuuvigerina*, *Tenuitella*, and *Cassigerinella*) and Problematica (*Dipsidripella* and *Tenuitella?*), in Pearson, P. N., Olsson, R. K., Hemleben, C., Huber, B. T., and Berggren, W. A. (eds.), Atlas of Eocene Planktonic Foraminifera: Cushman Foundation for Foraminiferal Research, Special Publication, no. 41, in press.
- JENKINS, D. G., 1966, Planktonic foraminiferal zones and new taxa from the Danian to lower Miocene of New Zealand: New Zealand Journal of Geology and Geophysics, v. 8, p. 1088–1126.
- , and ORR, W. N., 1972, Planktonic foraminiferal biostratigraphy of the east equatorial Pacific—DSDP Leg 9, in Hays, J. D., and others, Initial Reports of the Deep Sea Drilling Project: U.S. Government Printing Office, Washington, DC, v. 9, p. 1059–1193.
- KELLER, G., 1988, Extinction, survivorship and evolution of planktic foraminifers across the Cretaceous/Tertiary boundary at El Kef, Tunisia: Marine Micropaleontology, v. 13, p. 239–263.
- KELLY, D. C., 2002, Response of Antarctic (ODP Site 690) planktonic foraminifera to the Paleocene-Eocene thermal maximum: Faunal evidence for ocean/climate change: Paleoceanography, v. 17, no. 4, p. 23–1–23–13, 1071, doi:10.1029/2002PA000761.
- LI, Q., and RADFORD, S. S., 1992, Morphology and affinity of the planktonic foraminifer *Cassigerinelloita amekiensis* Stolk and reclassification of *Cassigerinelloita* Stolk, in Wise, S. W., Jr., Schlich, R., and others, Proceedings of the Ocean Drilling Program, Scientific Results: Ocean Drilling Program, College Station, Texas, v. 120, p. 595–602.
- LI, Q., RADFORD, S. S., and BANNER, F. T., 1992, Distribution of microperforate tenuitellid planktonic foraminifers in Holes 747A and 749B, Kerguelen Plateau, in Wise, S. W., Jr., and Schlich, R. (eds.), Proceedings of the Ocean Drilling Program, Scientific Results: Ocean Drilling Program, College Station, Texas, v. 120, p. 569–594.
- LU, G., and KELLER, G., 1993, The Paleocene-Eocene transition in the Antarctic Indian Ocean: Inference from planktic foraminifera: Marine Micropaleontology, v. 21, p. 101–142.
- MARTINI, E., 1971, Standard Tertiary and Quaternary calcareous nannoplankton zonation, in Farinacci, A. (ed.), Proceedings of the Second Planktonic Conference: Roma, 1970, Tecnoscienza, Edizioni Tecnoscienza, Roma, v. 2, p. 739–785.
- NAPOLEONE, G., PREMOLI SILVA, I., HELLER, F., CHELI, P., COREZZI, S., and FISCHER, A. G., 1983, Eocene magnetic stratigraphy at Gubbio, Italy, and its implications for Paleogene geochronology: Geological Society of America Bulletin, v. 94, p. 181–191.
- NOCCHI, M., AMICI, E., and PREMOLI SILVA, I., 1991, Planktonic foraminiferal biostratigraphy and paleoenvironmental interpretation of Paleogene faunas from the subantarctic transect, Leg 114, in Ciesielski, P. F., Kristoffersen, Y., and others, Proceedings of the Ocean Drilling Program, Scientific Results: Ocean Drilling Program, College Station, Texas, v. 114, p. 233–273.
- OLSSON, R. K., BERGGREN, W. A., HEMLEBEN, C., and HUBER, B. T., 1999, Atlas of Paleocene Planktonic Foraminifera, Smithsonian Institution Press, Washington, D.C., v. 85, p. 1–252.
- , HEMLEBEN, C., HUBER, B. T., and BERGGREN, W. A., 2005, Taxonomy, biostratigraphy, and phylogeny of Eocene *Globigerina*, *Globoturbotalita*, *Subbotina*, and *Turbotalita*, in Pearson, P. N., Olsson, R. K., Hemleben, C., Huber, B. T., and Berggren, W. A. (eds.), Atlas of Eocene Planktonic Foraminifera: Cushman Foundation for Foraminiferal Research, Special Publication, no. 41, in press.
- PEARSON, P. N., OLSSON, R. K., HEMLEBEN, C., HUBER, B. T., and BERGGREN, W. A. (eds.), 2005, Atlas of Eocene Planktonic Foraminifera, Cushman Foundation for Foraminiferal Research, Special Publication, no. 41, in press.
- PETRIZZO, M. R., 2004, Data report: Paleogene planktonic foraminiferal biostratigraphy at Holes 1209A, 1210A and 1211A (ODP Leg 198, Shatsky Rise), in Bralower, T. J., Premoli Silva, I., Malone, M. J., and others, Proceedings of the Ocean Drilling Program, Scientific Results, Ocean Drilling Program, College Station, Texas, v. 198, p. 1–29 [Online] available from World Wide Web: <http://www-odp.tamu.edu/publications/198_SR/102/102.htm>.
- QUILLÉVÉRÉ, F., 2000, Étude morphométrique et isotopique ($\delta^{18}\text{O}$, $\delta^{13}\text{C}$) de la diversification Paleocène du genre *Acarinina*: implications paléocéanographiques: Académie de Montpellier, Université Montpellier II, Sciences et Techniques du Languedoc, unpublished Ph.D. Thesis, Paleontology, 199 p.
- , and NORRIS, R. D., 2003, Ecological development of acarininids (planktonic Foraminifera) and hydrographic evolution of Paleocene surface waters, in Wing, S. L., Gingerich, P. D., Schmitz, B., and Thomas, E. (eds.), Causes and consequences of globally warm climates in the early Paleogene: Geological Society of America, Special Paper, no. 369, p. 223–238.
- , NORRIS, R. D., MOUSSA, I., and BERGGREN, W. A., 2001, Role of photosymbiosis and biogeography in the diversification of early Paleogene acarininids (planktonic foraminifera): Paleobiology, v. 27, p. 311–326.
- , AUBRY, M.-P., NORRIS, R. D., and BERGGREN, W. A., 2002, Paleocene oceanography of the eastern subtropical Indian Ocean; an integrated magnetobiostratigraphic and stable isotope study of ODP Hole 761B (Wombat Plateau): Palaeogeography, Palaeoclimatology, Palaeoecology, v. 184, p. 371–405.
- ROBERTS, A. P., BICKNELL, S. J., BYATT, J., BOHATY, S. M., FLORINDO, F., and HARWOOD, D. M., 2003, Magnetostratigraphic calibration of Southern Ocean diatom datums from the Eocene-Oligocene of Kerguelen Plateau (Ocean Drilling Program sites 744 and 748): Palaeogeography, Palaeoclimatology, and Palaeoecology, v. 198, p. 145–168.
- SHIPBOARD SCIENTIFIC PARTY, 2000, Leg 183 Summary: Kerguelen Plateau—Broken Ridge—A Large Igneous Province, in Coffin, M. F., Frey, F. A., Wallace, P. J. and others, Proceedings of the Ocean Drilling Program, Scientific Results, v. 183, [Online] available from World Wide Web: <http://www-odp.tamu.edu/publications/183_IR/183ir.htm>.
- SMIT, J., 1982, Extinction and Evolution of planktonic foraminifera after a major impact at the Cretaceous/Tertiary boundary, in Silver, L. T., and Schultz, P. H. (eds.), Geological Implications of Impacts of Large Asteroids and Comets on the Earth: Geological Society of America Special Paper 190, p. 329–352.
- SPEZZAFERRI, S., 1994, Planktonic foraminiferal biostratigraphy and taxonomy of the Oligocene and lower Miocene in the oceanic record. An overview: Palaeontographia Italica, v. 81, p. 1–187.
- SPIESS, V., 1990, Cenozoic magnetostratigraphy of leg 113 drill sites, Maud Rise, Weddell Sea, Antarctica, in Barker, P. F., Kennett, J. P., and others, Proceedings of the Ocean Drilling Program, Scientific Results: Ocean Drilling Program, College Station, Texas, v. 113, p. 261–315.
- STOLK, J., 1965, Contribution à l'étude des corrélations microfaunique du Tertiaire inférieur de la Nigérie méridionale: Bureau Recherches Géologiques Minérales Mémoire, v. 32, p. 247–267.
- STOTT, L. D., and KENNETT, J. P., 1990, Antarctic Paleogene planktonic foraminifer biostratigraphy: ODP Leg 113 sites 689 and 690, in Barker, P. F., Kennett, J. P., and others, Proceedings of the Ocean Drilling Program, Scientific Results: Ocean Drilling Program, College Station, Texas, v. 113, p. 549–569.
- THIERSTEIN, H. R., ASARO, F., EHRMANN, W. U., HUBER, B. T., MICHEL, H., SAKAI, H., and SCHMITZ, B., 1991, The Cretaceous/Tertiary boundary at Site 738, southern Kerguelen Plateau: Ocean Drilling Program, College Station, Texas, p. 849–867.
- WEI, W., and THIERSTEIN, H. R., 1991, Upper Cretaceous and Cenozoic calcareous nannofossils of the Kerguelen Plateau (southern Indian Ocean) and Prydz Bay (East Antarctica), in Barron, J., Larsen, B., and Baldauf, J., Proceedings of the Ocean Drilling Program, Scientific Results: Ocean Drilling Program, College Station, Texas, v. 119, p. 467–494.

Received 6 December 2004

Accepted 23 August 2005