

A REVISED CENOZOIC GEOCHRONOLOGY AND CHRONOSTRATIGRAPHY

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ABSTRACT: Since the publication of our previous time scale (Berggren and others, 1985c = BKFV85) a large amount of new magneto- and biostratigraphic data and radioisotopic ages have become available. An evaluation of some of the key magnetobiostratigraphic calibration points used in BKFV85, as suggested by high precision $^{40}\text{Ar}/^{39}\text{Ar}$ dating (e.g., Montanari and others, 1988; Swisher and Prothero, 1990; Prothero and Swisher, 1992; Prothero, 1994), has served as a catalyst for us in developing a revised Cenozoic time scale. For the Neogene Period, astrochronologic data (Shackleton and others, 1990; Hilgen, 1991) required re-evaluation of the calibration of the Pliocene and Pleistocene Epochs. The significantly older ages for the Pliocene-Pleistocene Epochs predicted by astronomical calibrations were soon corroborated by high precision $^{40}\text{Ar}/^{39}\text{Ar}$ dating (e.g., Baksi and others, 1992; McDougall and others, 1992; Tauxe and others, 1992; Walter and others, 1991; Renne and others, 1993). At the same time, a new and improved definition of the Late Cretaceous and Cenozoic polarity sequence was achieved based on a comprehensive evaluation of global sea-floor magnetic anomaly profiles (Cande and Kent, 1992). This, in turn, led to a revised Cenozoic geomagnetic polarity time scale (GPTS) based on standardization to a model of South Atlantic spreading history (Cande and Kent, 1992/1995 = CK92/95).

This paper presents a revised (integrated magnetobiochronologic) Cenozoic time scale (IMBTS) based on an assessment and integration of data from several sources. Biostratigraphic events are correlated to the recently revised global polarity time scale (CK95). The construction of the new GPTS is outlined with emphasis on methodology and newly developed polarity history nomenclature. The radioisotopic calibration points (as well as other relevant data) used to constrain the GPTS are reviewed in their (bio)stratigraphic context.

An updated magnetobiostratigraphic (re)assessment of about 150 pre-Pliocene planktonic foraminiferal datum events (including recently available high southern (austral) latitude data) and a new/modified zonal biostratigraphy provides an essentially global biostratigraphic correlation framework. This is complemented by a (re)assessment of nearly 100 calcareous nannofossil datum events. Unrecognized unconformities in the stratigraphic record (and to a lesser extent differences in taxonomic concepts), rather than latitudinal diachrony, is shown to account for discrepancies in magnetobiostratigraphic correlations in many instances, particularly in the Paleogene Period. Claims of diachrony of low amplitude (<2 my) are poorly substantiated, at least in the Paleocene and Eocene Epochs.

Finally, we (re)assess the current status of Cenozoic chronostratigraphy and present estimates of the chronology of lower (stage) and higher (system) level units. Although the numerical values of chronostratigraphic units (and their boundaries) have changed in the decade since the previous version of the Cenozoic time scale, the relative duration of these units has remained essentially the same. This is particularly true of the Paleogene Period, where the Paleocene/Eocene and Eocene/Oligocene boundaries have been shifted ~2 my younger and the Cretaceous/Paleogene boundary ~1 my younger. Changes in the Neogene time scale are relatively minor and reflect primarily improved magnetobiostratigraphic calibrations, better understanding of chronostratigraphic and magnetobiostratigraphic relationships, and the introduction of a congruent astronomical/paleomagnetic chronology for the past 6 my (and concomitant adjustments to magnetochron age estimates).

INTRODUCTION

The historical and methodologic background to the construction of the Paleogene (Berggren and others, 1985b = BKF85; Aubry and others, 1988) and Neogene (Berggren and others, 1985a = BKV85) components of an integrated Cenozoic time scale have been explained in detail. In the decade since the publication of our previous Cenozoic time scale (BKFV85), major advances in radioisotopic dating, magnetostратigraphy and (calcareous) plankton biostratigraphy, as well as the introduction of new approaches to geochronology (astrochronology; e.g., Shackleton and others, 1990; Hilgen, 1991) have forced a reevaluation and eventual updating of that study.

Cande and Kent (1992) presented a revised Cenozoic magnetochronology based on an evaluation of sea-floor magnetic anomalies. The geomagnetic polarity sequence was based primarily on data from the South Atlantic (with fine-scale data inserted from faster spreading regions of the Pacific and Indian Ocean) using a combination of finite rotation and averages of anomaly spacings from stacked profiles projected onto a synthetic sea-floor spreading flow line. The time scale was then generated by fitting a spline function to a set of nine age calibration points plus the zero-age ridge axis to the composite polarity sequence.

The present version of the global polarity time scale (GPTS) differs from that presented in Cande and Kent (1992) in the following respects: (1) the astronomical time scale values of polarity boundaries from Chron C1n to Subchron C3n.4n₍₀₎ (Thvera) (0–5.23 Ma) are accepted as standard which results in coherent and congruent magnetostratigraphic and astronomic chronologies back to 5.23 Ma, and (2) an age of 65.0 Ma is used for the Cretaceous/Paleocene (K/P) boundary (vs. 66.0 Ma in CK92). These changes, and the resulting modification to the GPTS, were revised in CK95.

We assess over 250 pre-Pliocene first-order (and to a lesser extent, second) correlations between calcareous plankton datum events and the GPTS, resulting in a significant improvement in biochronologic resolution and accuracy over a wide range of biogeographies and biostratigraphies compared to that proposed in 1985.

In recent years, we have witnessed a dramatic improvement in both geochronologic precision and accuracy (e.g., $^{40}\text{Ar}/^{39}\text{Ar}$ dating; astronomical chronology). The puzzling discordance between astrochronology and magnetochronology beyond ~3.5 Ma has been recently resolved and we can now look forward to the next generation of time scales, improvements to which we believe will come in the following areas: (1) extension of the astronomical time scale into the Miocene Epoch

(e.g., Krijgsman and others, 1994; Shackleton and others, 1995), (2) fine tuning of the chronology of the astronomical time scale (e.g., Langereis and others, 1994), and (3) application of Milankovitch climatic cyclicity for high-resolution relative chronology in older parts of the stratigraphic record (e.g., Herbert and d'Hondt, 1990).

In the discussion below and elsewhere in the text, repeated reference to various time scale studies has led us to use the following abbreviations for specific references (in addition to those listed above): HB78 for Hardenbol and Berggren (1978); GTS82 for Harland and others (1982) and GTS89 for Harland and others (1990).

GEOMAGNETIC POLARITY TIME SCALE

The first extended GPTS for the Cenozoic (and Late Cretaceous Period) era was based largely on a single magnetic anomaly profile from the South Atlantic (Heirtzler and others, 1968). The near-ridge axis polarity sequence was correlated to the independently developed radiometric polarity time scale (e.g., Cox and others, 1964), and the ages of older reversals were inferred by extrapolation from the older end of Anomaly 2A (Gilbert/Gauss boundary at ~ 3.4 Ma) assuming a constant rate of sea-floor spreading. Segments of the reversal sequence in the Neogene and Late Cretaceous Periods have been subsequently revised, for example, from Anomalies 1 to 3A (Klitgord and others, 1975), Anomalies 2 to 4A (Talwani and others, 1971), Anomalies 4A to 6 (Blakely, 1974), and Anomalies 30 to 34 (Cande and Kristoffersson, 1977) after the addition of Anomalies 33 and 34 (Larson and Pitman, 1972). These changes were incorporated in the revised time scale of LaBrecque and others (1977). The only modification made to the Paleogene sequence (\sim Anomalies 6C to 29) was the deletion of Anomaly 14 as an artifact.

Age calibration has been the focus of changes to the GPTS since the compilation of LaBrecque and others (1977). As additional age control became available based on developing magnetostratigraphic ties, the implicit assumption of constant spreading in the South Atlantic was relaxed to smaller time intervals (e.g., Ness and others, 1980; Lowrie and Alvarez, 1981; GTS82, GTS89; BK85; Haq and others, 1987, 1988).

For the first time since the magnetic anomaly time scale of Heirtzler and others (1968), the relative widths of the entire Late Cretaceous and Cenozoic polarity intervals were systematically determined from magnetic anomaly profiles (CK92). The geomagnetic polarity sequence was based primarily on data from the South Atlantic using a combination of finite rotation poles (Cande and others, 1988) and averages of anomaly spacings from stacked profiles projected onto a synthetic sea-floor spreading flowline. The South Atlantic has a long, continuous history of spreading that is well documented on both sides of the ridge axis, making it possible to compensate for asymmetric spreading, ridge jumps and similar processes that could distort the magnetic anomaly sequence. Finer scale information where necessary and possible was derived from magnetic profiles on faster spreading ridges in the Pacific and Indian Oceans and inserted into the framework of South Atlantic spreading. The composite reference sequence was scaled to distance from the ridge axis on a model flow line in the South Atlantic. The conversion of the anomaly sequence into a geomagnetic polarity

time scale is thus reduced to the determination of the seafloor spreading history in the South Atlantic.

In comparison to the frequency of geomagnetic reversals, there have been relatively few reliable, analytically precise and stratigraphically well-controlled radioisotopic ages available to establish a chronology: oceanic basalts, the source of the magnetic anomalies, are notoriously difficult to date isotopically, and datable horizons in magnetostratigraphic sections have been infrequently reported. Hence, time scales have relied on interpolation between selected calibration datums that have been correlated to the characteristic reversal pattern.

Cande and Kent (1992) assumed that spreading on the South Atlantic ridge system was smoothly varying but not necessarily constant over the Late Cretaceous and Cenozoic. A time scale of reversals was generated by interpolating the age of polarity intervals using a cubic spline function fitted to 9 age calibration-anomaly distance tie-points (plus the zero-axis ridge axis). This GPTS is referred to as CK92. A total of 92 normal polarity and a like number of reversed polarity intervals are recognized between the end of the Cretaceous Long Normal at 83.0 Ma and Chron C1n (Bruhn). The available magnetic anomaly data indicated that virtually all polarity intervals longer than ~ 30 ky are likely to have been identified. However, very short wavelength magnetic anomalies of ambiguous origin and with apparent durations less than 30 ky were not uniformly resolved over the entire anomaly sequence. These shortest features, numbering 54 in the present data, are referred to as cryptochrons and have been excluded from the GPTS.

To complement the comprehensive revision to the relative spacing of the polarity intervals, a revised polarity chron nomenclature was introduced. This scheme provides all polarity intervals with unique designations that is consistent with prior usage and that is amenable to accommodate further revision. This nomenclature, adapted from that used by Tauxe and others (1983), LaBrecque and others (1983) and Harland and others (1982, 1990), is described in detail in Cande and Kent (1992: Appendix) and only salient features are summarized here.

Because marine magnetic anomalies are effectively the standard global reference for geomagnetic reversals extending back to the Jurassic Period, the most useful polarity chron nomenclature is based on the numbered anomaly identifications (see Hailwood (1989) for a discussion of alternate schemes). For Late Cretaceous and Cenozoic time, prominent positive anomalies have been numbered (Pitman and others, 1968) from 1 (Central Anomaly) to 34 (younger end of the Cretaceous Quiet Zone). They are associated with oceanic crust magnetized more or less along the present field direction and correspond to time intervals (chrons) of normal geomagnetic polarity. Each of these intervals of predominantly normal polarity is designated by the anomaly number followed by the suffix *n*, whereas the preceding interval of predominantly reversed polarity is designated by the suffix *r*. For example, Chron C4n corresponds to Anomaly 4, and Chron 4r to the reversed interval between Anomalies 4 and 4A. When chrons are subdivided into shorter polarity intervals or subchrons, they are designated by a sequence number (from youngest to oldest within the chron) that is appended after a decimal point, with the suffix *n* for normal polarity and *r* for reversed polarity. For example, Chron C4n is subdivided into Subchrons C4n.1n, C4n.1r and C4n.2n, whereas Chron C4r is comprised of Subchrons C4r.1r, C4r.1n and C4r.2r. There will

aways be an odd number of polarity intervals within each chron so that the earliest subchron, if present, will not have a formally designated complementary interval of opposite polarity that is of comparable subchron rank. For example, it would be inappropriate to refer to Chron C4r as Subchron C4n.2r which is not formally recognized.

The young or old end of a chron or subchron can be conveniently designated by appending (y) or (o), respectively, as in Chron C4n(y) for the younger end of Chron C4n or the Chron C4n/Chron C3Br boundary. For more precise correlation, the relative or proportional position within a chron or subchron from its younger end can be specified by appending the equivalent decimal value within the parenthesis, as in Chron C4n(0.25) for one-quarter of the duration of Chron C4n from its young end.

An earlier system for identifying polarity chronos has traditionally been used for the radioisotopically dated part of the reversal time scale, i.e., the last ~ 5 my (Cox and others, 1964). Names of geomagneticians (Brunhes, Matuyama, Gauss and Gilbert) are used for the chronos (previously referred to as epochs), and names of localities (e.g., Jaramillo, Olduvai, etc.) for subchrons (previously referred to as events). This nomenclature is widely used and understood for magnetostratigraphic correlations in the Pliocene-Pleistocene Epochs and presents no conflict with the alternative magnetic anomaly system with which there is clear correlation. Efforts have been made to extend the magnetostratigraphic nomenclature below the Gilbert, by numbering intervals of alternating predominant polarity identified in deep-sea cores to about Chron 23, encompassing most of the Neogene Period (Theyer and Hammond, 1974; Opdyke and others, 1974). The magnetostratigraphic chronos, however, become increasingly difficult to correlate to the magnetic anomaly sequence below the Gilbert (implied as Chron 4) and are thus problematical in their utility for global correlation. To differentiate the anomaly designations for chronos from the superceded magnetostratigraphic numbering scheme that has been used in the literature (e.g., Ryan and others, 1974), the magnetic anomaly chronos have the prefix 'C' (LaBrecque and others, 1983), as in Chron C5n (a prominent normal polarity interval in the early late Miocene, which has variously been correlated to either Chron 9 or Chron 11) compared to Chron 5 (a predominantly normal polarity interval just prior to the Gilbert in the late Miocene and which is correlated to Chron C3An).

Since the publication of CK92, it has become apparent that the calibration tie-points at the Cretaceous/Paleocene boundary and in the Pliocene-Pleistocene Epochs should be modified. An age of 66 Ma for the Cretaceous/Paleocene (K/P) boundary was used in CK92, based on a chronogram estimate in GTS89 that was apparently supported by a series of high precision laser fusion Ar/Ar sanidine single crystal dates related to the iridium-bearing lower Z coal in Montana (see discussion in Berggren and others, 1992). The 66 Ma age for the K/P boundary, however, has become problematic because the 66 Ma dates from Montana are now believed to be systematically too old due to peculiarities of sample processing (Swisher and others, 1992). $^{40}\text{Ar}/^{39}\text{Ar}$ redating of the K/P boundary in Montana has yielded an age of ~ 65.0 Ma (Swisher and others, 1993). New, highly consistent $^{40}\text{Ar}/^{39}\text{Ar}$ dates on K/P boundary tektite glass from marine sections in Haiti and Mexico strongly suggest an age close to 65 Ma for the K/P boundary (Izett and others, 1991;

Swisher and others, 1992; Dalrymple and others, 1993; see also review in Item 1 in section on Radioisotopic Chronology below). A 65 Ma age is consequently now widely accepted for the K/P boundary and is used, for example, as a key tie-point in revisions to the Mesozoic geologic time scale (e.g., Gradstein and others, 1994; this volume).

In the Pliocene-Pleistocene Epochs, a new approach to geochronology has been to date high-resolution climate records by assuming that their characteristic variability is related to the well-known variations in Earth's orbital parameters, resulting in Milankovitch cyclicity. Unlike the discreteness of radioisotopic dates which requires interpolation using sedimentation or spreading rates to extend their range of usefulness, the astrochronologic method can effectively provide a continuum of independent age control, with a precision that is essentially a function of the shortest Milankovitch orbital variation (~ 20 -ky precession cycle) and an accuracy that ultimately depends on the reliability of the extrapolation of the modern orbital parameters back in time. On the basis of climatic records from the equatorial Pacific and the Mediterranean, astrochronologic control for geomagnetic reversals is now available to the Thvera (Subchron C3n.4n) in the early part of the Gilbert (Shackleton and others, 1990; Hilgen, 1991).

The astrochronologic estimates of Shackleton and others (1990) and Hilgen (1991) have been confirmed to ~ 3 Ma using high precision $^{40}\text{Ar}/^{39}\text{Ar}$ dating (e.g., Baksi and others, 1992; Tauxe and others, 1992; Walter and others, 1991; Renne and others, 1993; see also review in Item 7 in section on Radioisotopic Chronology, below). A comparison of the astrochronology with CK92 shows good agreement, typically to within 30 ky, to the earliest Gauss (Chron C2An) (Berggren and others, 1995). This is not unexpected because the direct calibration point at the Gauss/Matuyama boundary (Chron C2An(y)) in CK92 was based on this astrochronology. An appreciable discrepancy, however, appears in Chron C3n, where the astronomical time scale of Hilgen (1991) gives ages for the constituent subchrons (Subchrons C3n.1n, C3n.2n, C3n.3n, and C3n.4n, or Cochiti, Nunivak, Sidufjall, and Thvera, respectively) that are systematically 150 to 180 ky older than the interpolated ages in CK92. High precision radiometric dating that is relevant to this problem is presently lacking. However, it is now apparent that the magnetic anomaly sequence for this interval used by CK92 is the likely source of the problem. This was demonstrated by Wilson (1993) who showed that the astrochronology gives a more consistent spreading history when applied to a set of revised spacings of anomalies on the Cocos-Nazca and other Pacific spreading ridges.

The success of the continuous chronology provided by the Pliocene-Pleistocene astronomical time scale means that it is not necessary to interpolate between a few discrete dated levels to construct a geomagnetic polarity time scale, as has been done heretofore. Instead, the ages of reversals in the interval where astrochronology has been well developed simply become equivalent to the astrochronological values, thereby avoiding the promulgation of separate time scales. Astrochronological estimates are currently published for geomagnetic reversals back to the earliest Thvera Subchron (Subchron C3n.4n) (Shackleton and others, 1990; Hilgen, 1991), and these are considered to provide the best geomagnetic polarity time scale for the Pliocene-Pleistocene Epochs (Berggren and others, 1995). Older

than this, interpolation using marine magnetic anomalies is still necessary pending extension of the astrochronology.

A revised geomagnetic polarity time scale was generated using a radioisotopic age of 65 Ma rather than 66 Ma for the K/P boundary, and an astronomical age of 5.23 Ma (Hilgen, 1991) for the older end of Subchron C3n.4n (Thvera Subchron) rather than the age of 2.69 Ma for the younger boundary of Chron C2A (Gauss/Matuyama boundary) used in CK92, for the cubic spline interpolation. Calibration data (Table 1) are otherwise the same as by Cande and Kent (1992). The ages of Pliocene and Pleistocene polarity intervals, corresponding to Subchron C3n.4n and younger subchrons, are then inserted from the astrochronology of Shackleton and others (1990) and Hilgen (1991) with a refined astronomical age recently suggested for the Gauss/Matuyama boundary by Langereis and others (1994). With the revised K/P calibration, all of the 9 calibration tie points have direct marine biostratigraphic constraints for correlation. The revised geomagnetic polarity time scale (CK92/95) is listed for convenience with the age range and chron nomenclature of both normal polarity intervals (Table 2) as well as reversed polarity intervals (Table 3).

RADIOISOTOPIC CHRONOLOGY

In this section we discuss recent (mostly post-1990) radioisotopic data that have a bearing upon the revised integrated Cenozoic time scale presented here. Additional data, essentially presented between 1985 and 1990, were reviewed in Berggren and others (1992). Since the publication of BKF85, the field of geochronology has undergone a dramatic transformation culminating in the virtual replacement of conventional $^{40}\text{K}/^{40}\text{Ar}$ dating with $^{40}\text{Ar}/^{39}\text{Ar}$ dating as the primary method of choice in the calibration of the geologic time scale. This transformation has been a direct consequence of the development of low-blank high-resolution mass spectrometers. Coupled with micro-volume extraction lines, laser- and/or low blank furnace-heating, the $^{40}\text{Ar}/^{39}\text{Ar}$ dating method is capable of yielding highly reproducible ages (0.1% standard error on high potassium-bearing minerals) for much of the Cenozoic era. Automation of these dating systems further permits replicate ages to be easily obtained (a single age determination takes approximately 20 minutes), allowing recognition of multiple age components due to the presence of detrital crystals and/or alteration.

TABLE 1.—REVISED AGE CALIBRATIONS FOR GEOMAGNETIC POLARITY TIME SCALE, SOUTH ATLANTIC

Chron	Distance (km)	Age (Ma)
C3n.4n(o)	84.68	5.23*
C5Bn(y)	290.17	14.8
C6Cn.2r(y)	501.55	23.8
C13r.(14)	759.49	33.7
C21n.(33)	1071.62	46.8
C24r.(66)	1221.20	55.0
C29r.(3)	1364.37	65.0**
C33n.(15)	1575.56	74.5
C34n(y)	1862.32	83.0

*Ages for reversals for Subchron C3n.4n(o) and younger are made equivalent to astronomical time scale of Shackleton and others (1990) and Hilgen (1991), with refinement of Langereis and others (1994).

**Revised K/P boundary age, see text. Other age calibration data from Cande and Kent (1992).

TABLE 2.—NORMAL POLARITY INTERVALS.

Interval (Ma)	Chron
0.000–0.780	C1n (BRUNHES)
0.990–1.070	C1r.1n (Jaramillo)
1.201–1.211	C1r.2r-1n (Cobb Mountain)
1.770–1.950	C2n (Olduvai)
2.140–2.150	C2r.1n (Reunion)
2.581–3.040	C2An.1n (GAUSS)
3.110–3.220	C2An.2n (GAUSS)
3.330–3.580	C2An.3n (GAUSS)
4.180–4.290	C3n.1n (Cochiti)
4.480–4.620	C3n.2n (Nunivak)
4.800–4.890	C3n.3n (Sidufjall)
4.980–5.230	C3n.4n (Thvera)
5.894–6.137	C3An.1n
6.269–6.567	C3An.2n
6.935–7.091	C3Bn
7.135–7.170	C3Br.1n
7.341–7.375	C3Br.2n
7.432–7.562	C4n.1n
7.650–8.072	C4n.2n
8.225–8.257	C4r.1n
8.699–9.025	C4An
9.230–9.308	C4Ar.1n
9.580–9.642	C4Ar.2n
9.740–9.880	C5n.1n
9.920–10.949	C5n.2n
11.052–11.099	C5r.1n
11.476–11.531	C5r.2n
11.935–12.078	C5An.1n
12.184–12.401	C5An.2n
12.678–12.708	C5Ar.1n
12.775–12.819	C5Ar.2n
12.991–13.139	C5AAAn
13.302–13.510	C5ABn
13.703–14.076	C5ACn
14.178–14.612	C5ADn
14.800–14.888	C5Bn.1n
15.034–15.155	C5Bn.2n
16.014–16.293	C5Cn.1n
16.327–16.488	C5Cn.2n
16.556–16.726	C5Cn.3n
17.277–17.615	C5Dn
18.281–18.781	C5En
19.048–20.131	C6n
20.518–20.725	C6An.1n
20.996–21.320	C6An.2n
21.768–21.859	C6AAAn
22.151–22.248	C6AAr.1n
22.459–22.493	C6AAr.2n
22.588–22.750	C6Bn.1n
22.804–23.069	C6Bn.2n
23.353–23.535	C6Cn.1n
23.677–23.800	C6Cn.2n
23.999–24.118	C6Cn.3n
24.730–24.781	C7n.1n
24.835–25.183	C7n.2n
25.496–25.648	C7An
25.823–25.951	C8n.1n
25.992–26.554	C8n.2n
27.027–27.972	C9n
28.283–28.512	C10n.1n
28.578–28.745	C10n.2n
29.401–29.662	C11n.1n
29.765–30.098	C11n.2n
30.479–30.939	C12n
33.058–33.545	C13n
34.655–34.940	C15n
35.343–35.526	C16n.1n
35.685–36.341	C16n.2n
36.618–37.473	C17n.1n
37.604–37.848	C17n.2n
37.920–38.113	C17n.3n
38.426–39.552	C18n.1n
39.631–40.130	C18n.2n
41.257–41.521	C19n
42.536–43.789	C20n
46.264–47.906	C21n
49.037–49.714	C22n
50.778–50.946	C23n.1n

TABLE 2.—Continued.

Interval (Ma)	Chron
51.047–51.743	C23n.2n
52.364–52.663	C24n.1n
52.757–52.801	C24n.2n
52.903–53.347	C24n.3n
55.904–56.391	C25n
57.554–57.911	C26n
60.920–61.276	C27n
62.499–63.634	C28n
63.976–64.745	C29n
65.578–67.610	C30n
67.735–68.737	C31n
71.071–71.338	C32n.1n
71.587–73.004	C32n.2n
73.291–73.374	C32r.1n
73.619–79.075	C33n
83.000–118.000	C34n

The $^{40}\text{Ar}/^{39}\text{Ar}$ dating method differs from conventional $^{40}\text{K}/^{40}\text{Ar}$ dating in that samples to be dated are first irradiated in a nuclear reactor to convert a portion of ^{39}K to ^{39}Ar by nuclear bombardment of fast neutrons. This conversion permits the measurement of the potassium (now ^{39}Ar) content of the sample as well as the daughter radiogenic argon (^{40}Ar) to be made on the same sample aliquot, by the same method (mass spectrometry), at the same time. The assumption is that the $^{39}\text{K}/^{40}\text{K}$ ratio in nature has been essentially constant, the amount produced during irradiation being dependent upon the total amount of potassium present in the sample and the duration of neutron irradiation. Because the actual amount of ^{39}K converted to ^{39}Ar during irradiation is not known, the samples are irradiated with a fluence monitor mineral or standard of known age permitting the calculation of an irradiation coefficient, J , which is then applied to the unknowns.

The calibration of the fluence monitor mineral thus directly affects the accuracy of the $^{40}\text{Ar}/^{39}\text{Ar}$ ages calculated for the unknowns. The developments outlined above now permit $^{40}\text{Ar}/^{39}\text{Ar}$ ages with a precision that far exceeds the accuracy of the age of any currently available monitor mineral. For intercalibration purposes, most laboratories now report $^{40}\text{Ar}/^{39}\text{Ar}$ ages with reference to the age of international monitor minerals such as McClure Mountain Hornblende (MMhb-I) or Fish Canyon Tuff Sanidine (FCTS). At present, however, there appears to be no consensus among geochronologists as to the "correct" age of these monitor minerals. The reason for this is primarily historical. The ages of the $^{40}\text{Ar}/^{39}\text{Ar}$ monitor minerals are derived from the age of first principal $^{40}\text{K}/^{40}\text{Ar}$ standards calibrated directly against atmospheric air. Most first principal $^{40}\text{K}/^{40}\text{Ar}$ standards, however, are primarily Ar standards, used for the calibration of a ^{38}Ar spike or tracer. Thus while the radiogenic ^{40}Ar moles/g of the $^{40}\text{K}/^{40}\text{Ar}$ standard is well known, the ^{40}K content and consequently, the age of the standard, is not. The application of $^{40}\text{K}/^{40}\text{Ar}$ standards as $^{40}\text{Ar}/^{39}\text{Ar}$ monitor minerals in the calculation of the irradiation parameter J , requires that the age and, consequently, the ^{40}K be accurately known. The age of the $^{40}\text{Ar}/^{39}\text{Ar}$ monitor mineral directly affects the age of the unknown sample being dated. Currently, different laboratories report conflicting ages for international monitor minerals such as MMhb-I or FCTS, thus adding an unknown uncertainty to the accuracy of $^{40}\text{Ar}/^{39}\text{Ar}$ ages.

TABLE 3.—REVERSE POLARITY INTERVALS.

Polarity Interval (Ma)	Chron
0.780–0.990	C1r.1r (MATUYAMA)
1.070–1.201	C1r.2r.1r (MATUYAMA)
1.211–1.770	C1r.2r.2r (MATUYAMA)
1.950–2.140	C2r.1r (MATUYAMA)
2.150–2.581	C2r.2r (MATUYAMA)
3.040–3.110	C2An.1r (Kaena)
3.220–3.330	C2An.2r (Mammoth)
3.580–4.180	C2Ar (GILBERT)
4.290–4.480	C3n.1r (GILBERT)
4.620–4.800	C3n.2r (GILBERT)
4.890–4.980	C3n.3r (GILBERT)
5.230–5.894	C3r (GILBERT)
6.137–6.269	C3An.1r
6.567–6.935	C3Ar
7.091–7.135	C3Br.1r
7.170–7.341	C3Br.2r
7.375–7.432	C3Br.3r
7.562–7.650	C4n.1r
8.072–8.225	C4r.1r
8.257–8.699	C4r.2r
9.025–9.230	C4Ar.1r
9.308–9.580	C4Ar.2r
9.642–9.740	C4Ar.3r
9.880–9.920	C5n.1r
10.949–11.052	C5r.1r
11.099–11.476	C5r.2r
11.531–11.935	C5r.3r
12.078–12.184	C5An.1r
12.401–12.678	C5Ar.1r
12.708–12.775	C5Ar.2r
12.819–12.991	C5Ar.3r
13.139–13.302	C5AAr
13.510–13.703	C5ABr
14.076–14.178	C5ACr
14.612–14.800	C5ADr
14.888–15.034	C5Bn.1r
15.155–16.014	C5Br
16.293–16.327	C5Cn.1r
16.488–16.556	C5Cn.2r
16.726–17.277	C5Cr
17.615–18.281	C5Dr
18.781–19.048	C5Er
20.131–20518	C6r
20.725–20.996	C6An.1r
21.320–21.768	C6Ar
21.859–22.151	C6AAr.1r
22.248–22.459	C6AAr.2r
22.493–22.588	C6AAr.3r
22.750–22.804	C6Bn.1r
23.069–23.353	C6Br
23.535–23.677	C6Cn.1r
23.800–23.999	C6Cn.2r
24.118–24.730	C6Cr
24.781–24.835	C7n.1r
25.183–25.496	C7r
25.648–25.823	C7Ar
25.951–25.992	C8n.1r
26.554–27.027	C8r
27.972–28.283	C9r
28.512–28.578	C10n.1r
28.745–29.401	C10r
29.662–29.765	C11n.1r
30.098–30.479	C11r
30.939–33.058	C12r
33.545–34.655	C13r
34.940–35.343	C15r
35.526–35.685	C16n.1r
36.341–36.618	C16r
37.473–37.604	C17n.1r
37.848–37.920	C17n.2r
38.113–38.426	C17r
39.552–39.631	C18n.1r
40.130–41.257	C18r
41.521–42.536	C19r
43.789–46.264	C20r
47.906–49.037	C21r
49.714–50.778	C22r
50.946–51.047	C23n.1r

TABLE 3.—Continued.

Polarity Interval (Ma)	Chron
51.743–52.364	C23r
52.663–52.757	C24n.1r
52.801–52.903	C24n.2r
53.347–55.904	C24r
56.391–57.554	C25r
57.911–60.920	C26r
61.276–62.499	C27r
63.634–63.976	C28r
64.745–65.578	C29r
67.610–67.735	C30r
68.737–71.071	C31r
71.338–71.587	C32n.1r
73.004–73.291	C32r.1r
73.374–73.619	C32r.2r
79.075–83.000	C33r

Clearly, the “absolute” age of the $^{40}\text{Ar}/^{39}\text{Ar}$ monitor minerals is in serious need of review. In the interim, however, we stress the importance of internal consistency in the calibration of geological time scale tie-points. When it is deemed necessary to modify this calibration following refinements in the age of the standards, the time scale can be adjusted accordingly. Consequently, we would caution that any $^{40}\text{Ar}/^{39}\text{Ar}$ age used in comparison with this time scale must be adjusted to conform with the ages adopted here for the following international standards or monitor minerals: MMhb-I at 520.4 ± 1.7 Ma (Samson and Alexander, 1987), FCTS at 27.84 Ma (modified slightly from Cebula and others, 1986). The age used for one or both of these standards currently accompanies most $^{40}\text{Ar}/^{39}\text{Ar}$ dating studies which can be used for comparison with this time scale. Other frequently used ages for these standards seen in the literature that bear directly upon time scale calibration are those adopted by the Menlo Park U.S.G.S. laboratory at 513.9 ± 2.3 Ma and 27.55 ± 0.10 Ma, respectively, and the Australian National University at 524.2 Ma for MMhb-I.

Work in progress suggests that the older age reported for FCTS may be closer to its true geologic age. New $^{40}\text{K}/^{40}\text{Ar}$ ages for two biotite standards (the University of California, Berkeley GHC305 and the Australian National University GA1550) that are intercalibrated with FCTS by $^{40}\text{Ar}/^{39}\text{Ar}$, indicate the age of FCTS should be 28.05 ± 0.02 Ma (Swisher and others, 1994).

Independent support for this age comes from the age of FCTS predicted from the astronomically-calibrated geomagnetic polarity time scale (APTS) developed by Shackleton and others, (1990) and Hilgen (1991). The use of seven dated volcanic layers that can be directly tied to the APTS via magnetostratigraphy, and solving of the $^{40}\text{Ar}/^{39}\text{Ar}$ age equation for the age of FCTS required to produce ages for the volcanic layers coincident with those predicted by the APTS, yields mutually indistinguishable estimates for each of these seven reversals ranging from 27.78 to 28.09 Ma, with an inverse variance weighted mean of 27.95 ± 0.09 Ma (Renne and others, 1994). While we do not recommend the use of the APTS to calibrate the K/Ar system, the APTS can serve as an independent means of evaluating the accuracy in the calibration of radioisotopic decay systems. Additional intercalibration studies are needed to confirm this age.

We expect that there will be additional refinements in the age of $^{40}\text{Ar}/^{39}\text{Ar}$ fluence monitors over the next few years. The con-

version of the $^{40}\text{Ar}/^{39}\text{Ar}$ ages used in this time scale to a different monitor age can be achieved following Dalrymple and others, (1993):

$$t_2 = 1/l \log_e e^{l t_{m2}} - 1/e^{l t_{m1}} - 1(e^{l t_1} - 1) + 1]$$

where t_1 = the published age, t_{m1} = the age of the monitor used to obtain t_1 , t_{m2} = the new age for the monitor mineral, and t_2 = the converted age; l = the decay constant $5.543 \times 10^{-10} \text{ yr}^{-1}$.

The intercalibration of other geochronometers used in time scale calibration such as Rb-Sr, U-Pb and F-T faces similar problems and we caution the reader when comparing these different types of data. The accuracy and intercalibration of these geochronometers is beyond the scope of this paper, but will surely be the focus of studies in the near future.

Discussion of the Cenozoic radioisotopic data base is presented under seven items (older to younger) which correspond to seven of the nine calibration points (the other two calibration points are in the upper Cretaceous and beyond the scope of this paper) used in CK92, with modifications in CK92/95, and retained in this work.

Cretaceous/Paleogene (K/P) Boundary (Chron C29 to C28)

Much of the variation in currently available ages for the K/P boundary results primarily from interlaboratory differences in methodology and ages adopted for $^{40}\text{Ar}/^{39}\text{Ar}$ monitor minerals (Obradovich, 1984; Hall and others, 1991; Izett and others, 1991; Gillot and others, 1991; Swisher and others, 1992; McWilliams and others, 1992; Sharpton and others, 1992; Swisher and others, 1993; Dalrymple and others, 1993). However, $^{40}\text{Ar}/^{39}\text{Ar}$ dating has been shown to yield intralaboratory ages with reproducibility as low as 0.1% for K/P samples. Consequently, by minimizing variation due to calibration, it is possible for $^{40}\text{Ar}/^{39}\text{Ar}$ ages to provide precise tests of correlation between geographically distant sites and among various environments of deposition.

Compilations of the radioisotopic ages of the K/P boundary were recently made by Dalrymple and others (1993) and Swisher and others (1993, 1995); (Table 4). The extrapolated age for the K/P boundary at Agost, Spain, is 64.95 ± 0.07 Ma. The weighted mean of the $^{40}\text{Ar}/^{39}\text{Ar}$ ages compiled in Table 4 (omitting the age of the Chicxulub melt-rock because of lack of biostratigraphic control) is 65.06 ± 0.02 Ma. This age for the K/P boundary is in agreement with $^{40}\text{Ar}/^{39}\text{Ar}$ data for Haiti tektites from the U.S. Geological Survey, initially reported in Izett and others (1991) and subsequently thoroughly reviewed and summarized by Dalrymple and others (1993). For direct comparison with the above ages, the $^{40}\text{Ar}/^{39}\text{Ar}$ ages reported in Dalrymple and others (1993) are converted here using the above discussed algorithm for the monitor mineral Fish Canyon Tuff Sanidine at 27.55 Ma to 27.84 Ma (Table 5).

$^{40}\text{Ar}/^{39}\text{Ar}$ ages for the K/P boundary in the terrestrial record of eastern Montana are also summarized in Dalrymple and others (1993). The weighted mean of these analyses is 65.44 ± 0.07 Ma, slightly older than those obtained for the Haiti tektites. The differences are attributed by Dalrymple and others (1993) to be a result of imprecision in determining the neutron-efficiency factor, J , for the different irradiations and different sample positions and are not considered geologically significant.

TABLE 4.—SUMMARY OF $^{40}\text{Ar}/^{39}\text{Ar}$ LASER TOTAL FUSION AND INCREMENTAL HEATING AGES ASSOCIATED WITH IMPACT GENERATED SIGNATURES AT AGOST, SPAIN; EASTERN MONTANA, HAITI/MIMBRAL AND CHICXULUB (FROM SWISHER AND OTHERS, 1993, 1995).

Sample Location	Material Analyzed	Analysis Type	Total Number Of Analyses	Weighted Mean Age (Ma \pm SE ¹)
Spain, Agost	Biotite	TF	8	64.81 \pm 0.13 ²
Spain, Agost	Biotite	IH	1	64.86 \pm 0.09 ²
Montana, Ir.Z	Sanidine	TF	11	65.16 \pm 0.04 ²
Montana, Z-Hell Creek	Sanidine	TF	13	65.00 \pm 0.05 ²
Montana, Z-McGuire Creek	Sanidine	TF	20	65.03 \pm 0.04 ²
Haiti	Tektite glass	IH	7	65.01 \pm 0.08 ³
Haiti/Nimbral	Tektite glass	TF	5	65.07 \pm 0.10 ³
Mexico, Chicxulub	Melt-rock	IH	3	64.98 \pm 0.05 ³

TF = Laser Total Fusion $^{40}\text{Ar}/^{39}\text{Ar}$ analysis

IH = Laser Incremental Heating $^{40}\text{Ar}/^{39}\text{Ar}$ analysis

¹IH analyses are plateau ages

²Data from Swisher and others, 1995

³Data from Swisher and others, 1992

TABLE 5.—K/P BOUNDARY AGES FROM HAITI (DALRYMPLE AND OTHERS, 1993).

Sample Location	Material Anlyzed	Analysis Type	Total Number Of Analyses	Weighted Mean Age (Ma \pm SE ¹)
Haiti	Tektite glass	TF	52	65.09 \pm 0.06
Haiti	Tektite glass	IH	4	65.05 \pm 0.18
Haiti	Tektite glass	IH bulk	2	65.16 \pm 0.10

For example, if the analyses from one of the irradiations that yielded older ages are omitted from the calculation of the mean, the revised weighted mean, 65.20 ± 0.05 Ma, is within analytical error of the U.S. Geological Survey ages for the Haiti tektites.

These ages are approximately 1.0% younger than preliminary results reported in BKF85, Berggren and others (1992) and CK92. Some of the 66 Ma ages reported in Berggren and others (1992) and used in CK92 were derived from preliminary dating by Swisher (in Berggren and others, 1992). They are now known to be a result of an unorthodox method used in preparing samples from eastern Montana and are considered too old (Swisher and others, 1993). Although the K/P boundary itself was not used as a tie-point in BKF85, its broadly interpolated age of 66.4 Ma was supported by $^{40}\text{Ar}/^{39}\text{Ar}$ dates from K/P boundary sections in Montana and Colorado obtained by Obradovich (1984).

Gillot and others (1991) reported two $^{40}\text{K}/^{40}\text{Ar}$ ages on bulk samples of the Haiti tektites with a mean value of 64.0 ± 0.35 Ma. Other $^{40}\text{Ar}/^{39}\text{Ar}$ ages for the K/P boundary, reported in abstracts only, have yielded similar ages to those reported above. However, they are not further discussed as the data are unavailable for evaluation; these are the Haiti tektites (Hall and others, 1991), and the sanidines from Montana, Alberta and Saskatchewan (McWilliams and others, 1991a, b, 1992). The latter were from splits of K-Ar samples reported by Baadsgaard and others (1988).

$^{40}\text{Ar}/^{39}\text{Ar}$ dating of sanidine from units overlying the K/P boundary in the terrestrial record of eastern Montana in sections with magnetostratigraphy helps to constrain the age of the K/P boundary and provides additional calibration for Chrons C29 and C28. The weighted mean $^{40}\text{Ar}/^{39}\text{Ar}$ ages given in Table 6 are based on multiple analyses of single crystals of sanidine separated from bentonites interbedded in coal beds of the Tullock Formation, Garfield and McCone counties, eastern Mon-

tana (Swisher and others, 1993, 1995). According to these data, an age of ~ 64.6 Ma is suggested for Chron C29n(o), 64.1 Ma for Chron C29n(y), and 63.8 Ma for Chron C28n(o). These estimates are seen to be close to those estimated in CK92/95 based on a revised age of 65 Ma for the K/P boundary (Chron C29(o): 64.745 Ma; C29n(y): 63.976 Ma; Chron C28n(y): 63.634 Ma).

Paleocene/Eocene Boundary (Chron C24r)

Berggren and others (1992) reported a revised age estimate of 55 Ma for the Paleocene/Eocene boundary based primarily on the age of the Mo Clay, or -17 Ash in Denmark. A bulk incremental-heating $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age on sanidine of 55.07 ± 0.16 Ma was obtained by J. D. Obradovich (U.S.G.S., Denver; see Wing and others, 1991; Berggren and others, 1992). Additional laser total-fusion $^{40}\text{Ar}/^{39}\text{Ar}$ ages (Swisher and Knox, 1991; unpubl. data) on sanidine for the -17 Ash as well as its correlative N° 70 Ash in SE England gave concordant weighted mean ages of 54.51 ± 0.05 Ma and 54.56 ± 0.14 Ma, respectively. Also bearing on the age of the P/E boundary are laser total-fusion $^{40}\text{Ar}/^{39}\text{Ar}$ ages on sanidine from the Danish +19 Ash and its correlative N° 60 Ash in SE England that gave weighted mean ages of 54.0 ± 0.53 Ma and 54.04 ± 0.33 Ma, respectively. The -17 Ash coincides closely with the base of the London Clay Formation in SE England, and in DSDP Hole 550 it lies 7 m above the (unconformable) NP9/NP10 calcareous nannofossil zonal boundary and approximately 2/3 of the way down Chron C24r (see below for further discussion). An age of 55 Ma was estimated by Swisher and Knox (1991) for the NP9/NP10 zonal boundary and was utilized by CK92 as a calibration point and proxy for the Paleocene/Eocene boundary in the formulation of the GPTS.

The -17 Ash and the +19 Ash bracket the planktonic foraminiferal P5/P6a zonal boundary in DSDP Hole 550. The

TABLE 6.—AGES ON CHRONS C28 AND C29 IN THE TERRESTRIAL RECORD OF EASTERN MONTANA (SWISHER AND OTHERS, 1993, 1995).

Unit Name	Chron	Lab No	Total Number of Analyses	Age (Ma \pm SE)
U-Coal	C28r	6587	10	63.90 \pm 0.04
W-Coal	C29n	6584	15	64.13 \pm 0.04
		6753	20	64.09 \pm 0.03
HFZ-Coal	C29r	overall weighted mean	(35 analyses)	64.11 \pm 0.02
		6581	10	64.77 \pm 0.06
		6581 (plagioclase)	9	64.76 \pm 0.38

Paleocene/Eocene boundary which awaits determination of a global stratigraphic section and point (GSSP) is bracketed by the P5/P6a zonal boundary (LAD of *Morozovella velascoensis*) and the $\delta^{13}\text{C}$ spike (and associated events) in mid-Zone NP9. The “boundary interval” encompasses the NP9/NP10 calcareous nannofossil zonal boundary at \sim 55 Ma and the base of the London Clay Formation (see Berggren and Aubry, 1995, and Aubry and others, 1995, for further discussion). These ages aid in constraining the age of the Paleocene/Eocene boundary provisionally taken at the base of the London Clay Formation, which now differs significantly (\sim 54.8 Ma, based on sediment rate interpolation in DSDP Hole 550; see Berggren and Aubry, 1995, for discussion of this estimate) from the estimates of 57.8 Ma in BKF85 and 57 Ma in Aubry and others (1988).

Early Middle Eocene Epoch (Chron C21n)

K/Ar dating of a biotite recovered from DSDP Hole 516F-76-4, 107–115 cm, gave dates of 45.8 ± 0.5 Ma and 46.8 ± 0.5 Ma (Bryan and Duncan, 1983). The biotite was recorded as occurring within an interval identified as Zone P10 and lower part of Zone NP15 (Barker and others, 1983; Wei and Wise, 1989). The interval falls within a normal polarity magnetozone correlated with the mid to upper part of Chronozone C21n (Berggren and others, 1983b; Berggren and others, 1985b; Berggren and others, 1992; Aubry, this volume). In constructing the GPTS, CK92 used 46.8 Ma as a calibration for the mid-younger part of Chron C21n (see Table 1). A small amount of the rock from this interval was made available to us by A. Montanari for $^{40}\text{Ar}/^{39}\text{Ar}$ dating. $^{40}\text{Ar}/^{39}\text{Ar}$ laser total-fusion analyses of sanidine and biotite from this same interval yielded dates concordant with the younger biotite date reported by Bryan and Duncan (1983). The weighted mean ages of the analyses are 45.66 ± 0.05 Ma and 45.60 ± 0.20 Ma, respectively (Swisher and Montanari, in prep.).

The $^{40}\text{Ar}/^{39}\text{Ar}$ ages for the lower part of planktonic foraminiferal Zone P10, lower part of calcareous nannofossil Zone NP15, and mid to upper Magnetic Polarity Chronozone C21n are supported by a number of K/Ar dates on biotite and glauconite from the Gulf and Atlantic Coastal Plain. They are, however, significantly older than Rb/Sr ages from the same samples. Harris and Fullagar (1989, 1991) in their review of the Gulf and Atlantic Coastal Plain Rb/Sr and K/Ar data on stratigraphic levels correlative with Zone NP15, show clearly that $^{40}\text{K}/^{40}\text{Ar}$ dating has yielded dates in the range of 46–47 Ma, whereas Rb/Sr dates are centered on 42–45 Ma. Thus, while there is a slight degree of overlap in the two data sets, it is clear that, for the most part, the K/Ar dates are, on average, 1 to 2 my older than the Rb/Sr dates. One possible explanation for this difference could reside in the difference in calibration of the K/Ar and Rb/Sr systems.

Since BKF85, Harris and Fullagar (1991) reported a Rb/Sr isochron date of 41.6 ± 1.5 Ma on the Warley Hill Formation (=Zone NP15), which is substantially younger than the age span of \sim 44–47.5 Ma that conversion of the chronology of Zone NP15 (in BKF85) to this time scale suggests. Harris and Fullagar (1991) observed that the two K/Ar dates of 43.5 ± 1.7 Ma and 46.6 ± 1.8 Ma are in analytic agreement with each other and that the younger of these two dates is in essential agreement with a previously published (Harris and Fullagar, 1989) Rb/Sr date of 42.0 ± 0.5 Ma on glauconites at Wilson’s Landing which were correlated to the type locality of the Warley Hill Formation, Calhoun County, South Carolina. The older conventional K/Ar date (46.6 ± 1.8 Ma) does not agree analytically with the Rb/Sr date(s) but falls within the limits estimated here for the lower part of Zone NP15 as well as with those in HB78, BKF85 and Haq and others (1987, 1988). The older conventional K/Ar date is, however, consistent with K/Ar ages reported by Harris and Fullagar (1989) for Zone NP15 from the Castle Hayne Limestone of the Atlantic Coastal Plain. K/Ar ages on biotite from a bentonite and on glauconite below it yielded similar ages of 46.2 ± 1.8 Ma and 46.7 ± 1.8 Ma. Rb/Sr isochron ages on the same biotite and glauconite yielded consistently younger ages of 45.7 ± 0.7 Ma and 45.3 ± 0.3 Ma, respectively. It also yielded Rb/Sr and K/Ar ages on a glauconite overlying the bentonite of 43.1 ± 1.2 Ma and 44.5 ± 1.7 Ma. These findings are consistent with the anomalously younger Rb-Sr isochron age of 41.6 ± 1.5 Ma for the Warley Hill Formation. However, Harris and Fullagar (1991) noted that previously published Rb/Sr and K/Ar dates on younger stratigraphic units containing (or stratigraphically correlative with) *Cubitostrea sellaeformis* (in calcareous nannofossil Zone NP16) are essentially in agreement over the interval of \sim 39–42 Ma. In summary, the K/Ar dates reported on Zone NP15 by Harris and Fullagar (1989, 1991) are in agreement with the $^{40}\text{Ar}/^{39}\text{Ar}$ ages discussed above. Also, they are more reliable and agree more closely with the revised estimated age span of Zone NP15 than do the Rb/Sr dates.

Volcanic activity built up a shallow marine edifice at ODP Site 713 that yielded a weighted mean whole rock $^{40}\text{Ar}/^{39}\text{Ar}$ age of 49.3 ± 0.6 Ma (Duncan and Hargraves, 1990). Sediments interbedded with these basalts yield calcareous nannofossil assemblages indicative of Subzone CP13b (Subzone NP15b), and the reversed magnetized basalts are correlated with Chron C20r in BKF85. Given the current age calibration for Chron C20 presented here, in Berggren and others (1992), and used in CK92/95, the age of the Site 713 basalts appears too old.

Eocene/Oligocene Boundary (Chron C13r)

The calibration of the Eocene/Oligocene boundary at 33.7 Ma used in CK92 and retained here is discussed thoroughly in

Berggren and others (1992). Indeed, the history of radioisotopic studies for the early middle Eocene Epoch (Chron C21n) and bracketing the Eocene/Oligocene boundary (Chron C13r) which led to the revised GPTS of CK92/95, and, ultimately, this paper, has been reviewed in detail by Prothero (1994). Additional age data published since on bentonites from the upper Eocene Yazoo Formation, west-central Mississippi, assigned to planktonic foraminifera Zone P17 and to Chron C13r, were reported in Obradovich and others (1993). A single incremental-heating experiment (J.D.O.) on sanidine (Sample 1 of *Satartia*) yielded a plateau age of 34.32 ± 0.05 Ma. Laser total-fusion analyses (C.C.S.) of the sanidine from the same unit yielded a weighted mean age of 34.30 ± 0.06 Ma, while biotite from the nearby Society Ridge Core, level 80.0–81.0 feet, yielded a concordant age of 34.29 ± 0.11 Ma. The overall weighted mean of the analyses of 34.31 ± 0.04 Ma provides additional calibration of Zone P17 and Chron C13r.

Oligocene/Miocene Boundary (Chron C6Cn)

CK92 used the Chron C6Cn.2n/r boundary as a mid-Cenozoic calibration point for the Cenozoic time scale. CK92 cited BKF85 for an estimate of 23.7 Ma and the chronogram estimate of 23.8 Ma from GTS89 as the age of the Oligocene/Miocene boundary. A GSSP for the Oligocene/Miocene boundary is currently being proposed at the Chron C6Cn.2n/r boundary in the Carrioso-Lemme Section, NE Italy (Steininger, 1994) and this proposal is accepted here.

Miocene Epoch (Chron C6Cn to Chron C3r)

The CK92/95 age for the Oligocene/Miocene boundary is consistent with dating of the Livello Raffaello Tuff in the Contessa CQ-CT section, Italy, by Montanari and others (1991). This tuff yields a mean $^{40}\text{Ar}/^{39}\text{Ar}$ age of 21.17 ± 0.23 Ma. It occurs in sediments with reversed polarity correlated in conjunction with biostratigraphic constraints with Chron C6Ar which has age limits of 21.320 to 21.768 Ma in our time scale.

CK92 incorporated an age of 14.8 Ma for the younger end of Chron C5Bn. This age is based on age constraints on the correlative N9/N10 foraminiferal zonal boundary (Miller and others, 1985; Berggren and others, 1985a) as estimated in Japan at 14.6 ± 0.4 Ma (Tsuchi and others, 1981; Saito, 1984) and in Martinique at 15.0 ± 0.3 Ma (Andreieff and others, 1976; pers. commun. in BKF85).

An alternative calibration for Chron C5Bn has been recently proposed by Baksi (1993, and refs. therein) largely on the basis of geomagnetic polarity and $^{40}\text{Ar}/^{39}\text{Ar}$ age data from the Columbia River Basalts (CRB), primarily from that of the Imnaha, Grande Ronde and Steen Basalts. Ages derived from $^{40}\text{Ar}/^{39}\text{Ar}$ incremental-heating of whole rock basalts led Baksi (1993) to suggest that Chron C5Bn is approximately 7% (or approximately 1 my) older than that indicated by CK92.

A key calibration point of the revised time scale proposed by Baksi (1993) is the CRB N₁-R₁ transition dated at 16.32 ± 0.1 Ma and thought to correspond to Chron C5Bn(o) and ~1.2 my older than Chron C5Bn(o) in CK92 or CK92/95. This age is approximately 0.8 my older than the $^{40}\text{K}/^{40}\text{Ar}$ age (15.5 ± 0.3 Ma) reported for this transition (Baksi and others, 1967) and ~0.2 my older than the previously reported $^{40}\text{Ar}/^{39}\text{Ar}$ age (Baksi and Farrar, 1990). As pointed out by Baksi and Farrar (1990),

however, the accuracy of the CRB calibration of the GPST requires that the magnetic polarities of the CRB are stratigraphically unique, that no magnetic polarity unit greater than 0.1 my is missing, that the correlation of the CRB polarity transitions to the GPTS are correct, and that the newly revised $^{40}\text{Ar}/^{39}\text{Ar}$ ages are accurate.

Against the older age of the proposed calibration point for Chron C5Bn in Baksi (1993) and in addition to the above mentioned ages from Japan and Martinique, we cite the $^{40}\text{K}/^{40}\text{Ar}$ and $^{40}\text{Ar}/^{39}\text{Ar}$ data from the continental Barstow Formation of southern California (MacFadden and others, 1990). These authors reported ages of 15.9 ± 0.06 Ma on a tuff located within Chron C5Br, 14.8 ± 0.06 Ma on a tuff located within Chron C5ADr, and 14.0 ± 0.09 Ma on a tuff located within Chron C5ACn. For the interval between 16 to 14 Ma, the Barstow data agree quite well with the predictions of CK92/95. However, if we attempt to correlate the Barstow tuffs with the time scale proposed by Baksi (1993), each of the Barstow tuffs is predicted to occur either in intervals of opposite polarity from that observed, or at reversal boundaries.

Another calibration point used by Baksi (1993) is a reversed-normal transition recorded in the Akaroa volcanic field, New Zealand, which Baksi and others (1993a) correlate with the top of Chron C5n. Three basalts spanning this transition yielded a mean age of 9.67 ± 0.11 Ma. We note that this suggested younger limit of Chron C5n is consistent with that of 9.74 Ma in this work and of 9.6 Ma by McDougall and others (1984) from Icelandic basalts. However, we note that the reversed-normal transition in the Akaroa volcanic field can be correlated either with the Chron C5n.1r/C5n.2n or the Chron C4Ar.2 r/n boundary.

We conclude that the time scale that Baksi (1993) proposed for the ~10–17 Ma interval suffers from ambiguous correlation of isolated magnetic reversals with the GPTS. For example, assuming that the new $^{40}\text{Ar}/^{39}\text{Ar}$ ages of Baksi (1993) are accurate, an alternative correlation for the dated CRB units would be that the N₁-R₁ transition dated at 16.32 ± 0.1 Ma correlates with one of the short reversed intervals within Chron 5Cn and that the CRB R₁-N₀ transition, dated at 17.5 ± 0.2 Ma, correlates with Chron C5Cr/C5Dn. This revised interpretation would be consistent with the CK92/95 ages in this interval. However, this would imply that the erosional unconformity between the Grande Ronde and Wanapum basalts represents more time than previously recognized or that the poorly calibrated Wanapum basalts are in need of $^{40}\text{Ar}/^{39}\text{Ar}$ dating.

We also cite ten $^{40}\text{Ar}/^{39}\text{Ar}$ dates on the magnetostratigraphically measured sanidine-bearing tuffs of the Ngorora Formation, Kenya (Deino and others, 1990). These range between 13.0 Ma at the base of Chron C5AA and 11.7 Ma at the top of Chron C5A. Correlation of the magnetostratigraphy of the Ngorora Formation with the time-scale proposed by Baksi (1993) results in opposite polarity assignments for the $^{40}\text{Ar}/^{39}\text{Ar}$ ages obtained on interbedded tuffs.

An age of 7.26 ± 0.1 Ma for the Tortonian/Messinian boundary in the northern Apennines of Romagna was recently suggested by Vai and others (1993) based on a K/Ar (biotite) and a $^{40}\text{Ar}/^{39}\text{Ar}$ (plagioclase) date of 7.33 Ma on volcanogenic horizons a few meters below the FAD of *Globorotalia conomiozea* and *Gt. mediterranea* and a K/Ar (biotite) date of 7.72 ± 0.15 Ma on the stratigraphically lower FAD of *Globorotalia suterae*

(which agrees closely with the magnetostratigraphic estimate for this datum event proposed here). The radioisotopic age estimate of 7.26 Ma for the Tortonian/Messinian boundary is seen to agree closely with the magnetostratigraphic age estimate of 7.12 Ma in this paper.

Pliocene-Pleistocene Epochs (Chron C1 to Chron C3 = Brunhes to Gilbert)

The youngest calibration point used in virtually all previous time scales is the Gilbert/Gauss boundary. Based on conventional $^{40}\text{K}/^{40}\text{Ar}$ dates, Mankinen and Dalrymple (1979) estimated the age of the Gilbert/Gauss (Chrons C2An/C2Ar) boundary to be 3.40 Ma. However, age estimates for this boundary based on astronomical predictions suggest that the age of many of the Plio-Pleistocene geomagnetic reversal boundaries as calibrated by conventional $^{40}\text{K}/^{40}\text{Ar}$ dates are too young. The astronomical predictions are derived by assuming that the variability recorded in high-resolution climatic records was forced by the well-known variations in the Earth's orbital parameters. Forcing the climatic records from the equatorial Pacific (Shackleton and others, 1990) and the Mediterranean region (Hilgen, 1991) to fit with the Earth's orbital parameter variations, suggests that the conventional K/Ar ages reported by Mankinen and Dalrymple (1979) for the estimation of the age of Plio-Pleistocene magnetic reversal boundaries were indeed too young by ~5 to 7%. As a consequence of these studies, the CK92 time-scale departed from the conventional use of only radioisotopic data and incorporated the astronomical data for the calibration of the Pliocene-Pleistocene Epochs (Cande and Kent, 1992). CK92 used the astronomically derived age of the Gauss/Matuyama boundary (= C2An(y)) as determined independently by both Shackleton and others (1990) and Hilgen (1991) at 2.60 Ma. The astronomically derived age is approximately 5% older than the 2.48 Ma estimate for the Gauss/Matuyama boundary based on previously reported K/Ar data (Mankinen and Dalrymple, 1979). More recently, Langereis and others (1994) provided a refined astronomically derived age of 2.581 Ma for the Gauss/Matuyama boundary.

Recent $^{40}\text{Ar}/^{39}\text{Ar}$ dating of stratigraphic levels representative of the last 4 my of the Neogene Period now confirms the astronomical age predictions based on high-resolution climatic records for the Pliocene-Pleistocene Epochs. In a series of recent papers, conventional $^{40}\text{K}/^{40}\text{Ar}$ ages on anorthoclase (McDougall and others, 1992) as well as both $^{40}\text{Ar}/^{39}\text{Ar}$ incremental-heating of bulk separates and replicate laser total-fusion of single volcanic crystals (Baksi and others, 1992; Baksy, and others, 1993b; Izett and Obradovich, 1991; Renne and others, 1993; Spell and McDougall, 1992; Spell and Harrison, 1993; Tauxe and others, 1992; Turrin and others, 1994; Izett and Obradovich, 1994) now indicate congruence between the astronomically and radioisotopically derived ages for the Plio-Pleistocene interval. Accordingly, we have adopted the astronomical time scale of Shackleton and others (1990) and Hilgen (1991) as standard for the interval Chron C1-Chron C3 (0 to 5.23 Ma). Table 7 summarizes these data (see also Berggren and others, 1995).

INTEGRATED CENOZOIC MAGNETOBIOCHRONOLOGY

At this point, we introduce the revised, integrated Cenozoic magnetobiochronologic scale which has resulted from our com-

TABLE 7.—ISOTOPIC VS. ASTRONOMICAL AGES FOR EARLY PLIOCENE-PLEISTOCENE MAGNETOCHRONS.

Chron	Radioisotopic Age Estimates	Astronomically Estimated Ages
C1n/lr (= Brunhes/Matuyama)	>0.746 ¹ >0.780 ² >0.783 ³ ~0.780 ⁴	0.780 ⁸
C1r.1n (Jaramillo)	0.992-? ¹	0.990-1.070 ^s
C2n (Olduvai)	1.78-1.96 ⁴	1.79-1.95 ^H 1.95-1.77 ^S
C2An.1n	2.60-3.02 ⁴	2.60-3.04 ^H
C2An.2n	3.09-3.21 ^{4,5}	3.11-3.22 ^H
C2An.3n	3.29-3.57 ^{4,5}	3.33-3.58 ^H

¹Tauxe and others, 1992

²Izett and Obradovich, 1991

³Baksi and others, 1992

⁴Spell and McDougall, 1992, and Spell and Harrison, 1993

⁵McDougall and others, 1992

⁶Renne and others, 1993

⁷Shackleton and others, 1990

⁸Hilgen, 1991

bined efforts (Figs. 1-6). In this way, the time scale figures can serve as a link between the geomagnetic polarity/sea-floor anomaly and radioisotopic data base which have been discussed above and the revised correlation and calibration of planktonic foraminiferal and calcareous nannofossil biostratigraphic datum events to the GPTS, which are discussed below. The planktonic foraminiferal and calcareous nannofossil datum events which have served to construct the magnetobiochronologic framework we present are discussed in Tables 8 to 13 and 14 to 17, respectively.

Planktonic Foraminiferal Biostratigraphy

Paleogene Zonation.—

The Paleogene planktonic foraminiferal zonation of Berggren and Miller (1988) is adopted here for essentially tropical-subtropical stratigraphies (with modifications noted below). At high austral latitudes a Paleogene scheme has been developed by Stott and Kennett (1990) and modified by Huber (1991) or augmented by Berggren (1992). Cross correlation of these zonal stratigraphies is afforded, in some instances, by means of magnetostratigraphy but in other cases problems in taxonomy (particularly among Paleocene and Eocene acarininids) or lack of precise magnetobiostratigraphic calibration hinder true interhemispherical correlation and calibration (see also relevant comments by Bolli and Krasheninnikov, 1978 from an earlier period of studies). Zonal magnetobiochronology has been based, as in the case of BKF85, on a compilation and evaluation of first-order correlations between biostratigraphic datums and magnetostratigraphy in DSDP and ODP boreholes as well as landsections. Our own studies on planktonic foraminiferal biostratigraphy (WAB) have been incorporated in this study where relevant. For example, Paleocene planktonic foraminiferal stratigraphy of DSDP/ODP Holes 384 (NW Atlantic), 577 and 465 (western Pacific), 213, 758 and 761 (Indian Ocean) and 750A (Kerguelan Plateau) have been studied in detail to supplement existing data. A paleomagnetic record spanning virtually the entire Paleocene in DSDP Hole 384 (Berggren and others, 1994) has provided a much needed improvement to first-order

PALEOCENE TIME SCALE

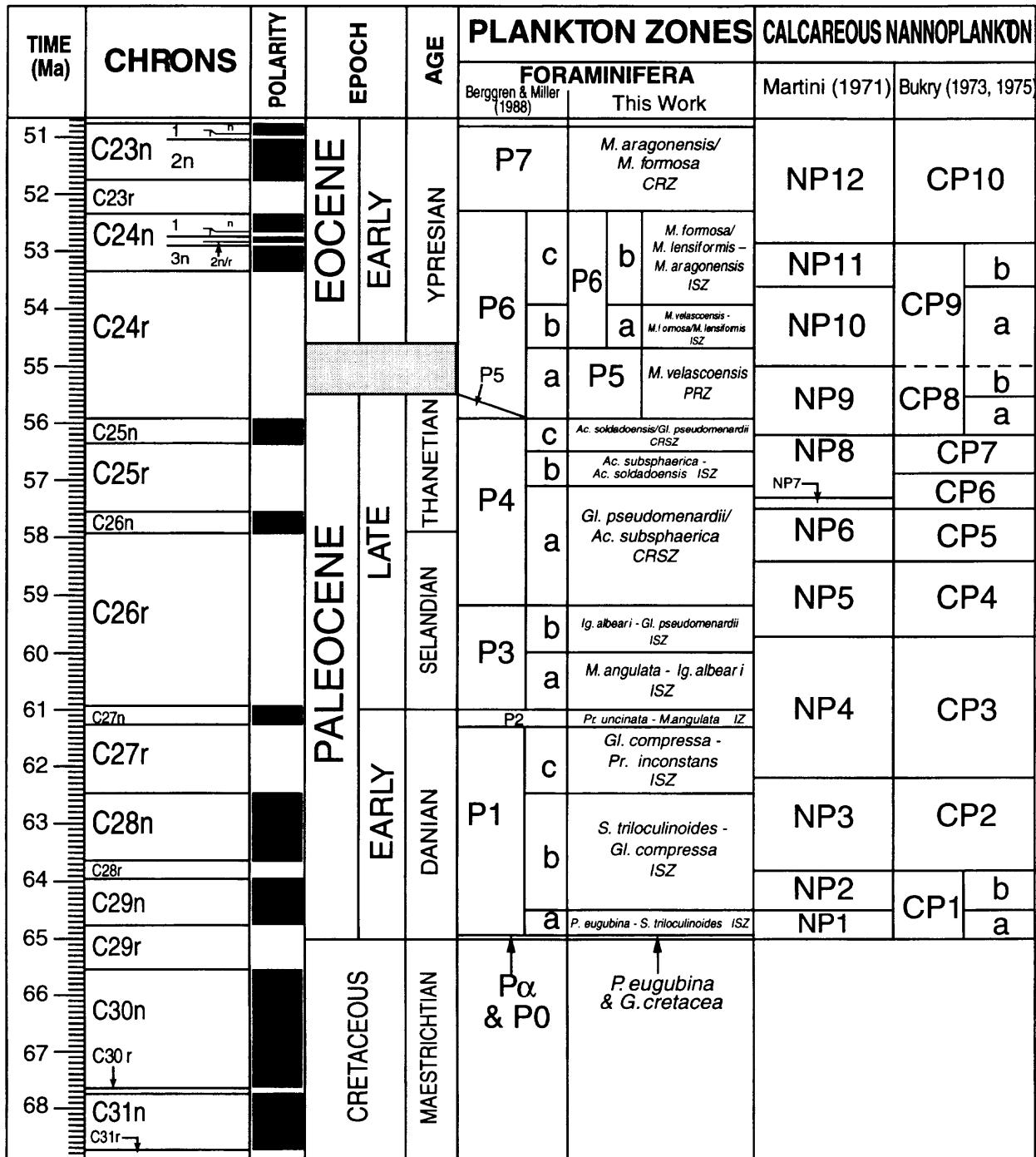


FIG. 1.—The chronology of the Cenozoic Era (and its chronostratigraphic subdivisions) presented in this paper has been developed by fitting a spline fit to a set of 9 calibration points (described in greater detail in the section on the geomagnetic polarity time scale) and represents a modification of the chronology of CK92 to that of CK92/95. The various datum events used to define the Paleogene and Neogene planktonic foraminiferal biostratigraphic zones have then been correlated to the resulting magnetostratigraphy resulting in a magnetobiochronology. Most of the correlations are by direct, first-order correlation (see Tables 8 to 17); others represent indirect, second-order correlations. The relatively broad gray band spanning the interval between ~54.6 to 55.5 Ma reflects current opinion on the position of the Paleocene/Eocene boundary. Taken at the base of the type Ypresian in the Belgian basin or the base of the London Clay in the London-Hampshire Basin its position would be at ~54.6 Ma to 54.8 Ma, respectively. Planktonic foraminiferal specialists commonly use the P5/P6 boundary (~54.7 Ma) and calcareous nannoplankton specialists the NP9/NP10 zonal boundary (~55.0 Ma) as denotative of the boundary for purpose of correlation. More recently the major $\delta^{13}\text{C}$ spike at ~55.5 Ma has been suggested as providing a useful means of correlation between marine and terrestrial stratigraphies. Lacking a clearly defined Global Stratotype Section and Point (GSSP), the Paleocene/Eocene boundary awaits an unequivocal definition (IGCP Project 308) in 1996. See text for further discussion of the intricate (bio)stratigraphic problems associated with the Paleocene/Eocene boundary. The other epoch/series boundaries of the Cenozoic Era have GSSP's so that physical position and corresponding age estimates are relatively well established.

EOCENE TIME SCALE

TIME (Ma)	CHRONS	POLARITY	EPOCH	AGE	PLANKTON ZONES		CALCAREOUS NANNOPLANKTON	
					Berggren & Miller (1988)	FORAMINIFERA This Work	Martini (1971)	Bukry (1973, 1975)
31	C12n		OOLIGO-	P19		<i>T. ampliapertura</i> IZ		
32	C12r		CENE			<i>Ch. cubensis</i> – <i>Pseudohastigerina</i> spp IZ		
33	C13n			P18				
34	C13r		LATE	P17		<i>T. cerroazulensis</i> IZ	NP21	
35	C15n			P16		<i>T. cunialensis/Cr. inflata</i> CRZ		
36	C15r						NP19-20	CP15
36	C16n	1 n	PRIABONIAN	P15		<i>Po. semiinvoluta</i> IZ	NP18	
37	C16r	2 n						
37	C17n	1 n		P14		<i>Tr. rohri</i> – <i>M. spinulosa</i> PRZ	NP17	b
38	C17r	2 n		P13		<i>Gb. beckmanni</i> TRZ		
39	C18n	1 n					NP16	a
40	C18r	2 n						
41	C19n		MIDDLE	P12		<i>M. lehneri</i> PRZ		
42	C19r						NP15	c
43	C20n			P11		<i>Gb. kugleri</i> / <i>M. aragonensis</i> CRZ		b
44	C20r							a
45	C21n		LUTETIAN	P10		<i>H. nuttalli</i> IZ	NP14	c
46	C21r							b
47	C22n			P9		<i>Pt. palmerae</i> – <i>H. nuttalli</i> IZ	NP13	a
48	C22r			P8		<i>M. aragonensis</i> PRZ		
49	C23n	1 n		P7		<i>M. aragonensis/M. formosa</i> CRZ	NP12	CP11
50	C23r	2 n						
51	C24n	1 n	YPRESIAN	P6	c	<i>M. formosa/M. lensiformis</i> <i>M. aragonensis</i> ISZ	NP11	b
52	C24r	2 n		P6	b	<i>M. velascoensis</i> – <i>M. formosa/M. lensiformis</i> ISZ	NP10	a
53	C25n	1 n		P5	a	<i>M. velascoensis</i> IZ	NP9	b
54	C25r	3 n				<i>M. soldadoensis/Gl. pseudomenardii</i> CRSZ		a
55			PALEO-					
56			CENE					
			LATE					
			THANE-					
			TIAN					
				P4	c			

FIG. 2.—See Figure 1 for further explanation.

magnetobiostratigraphic correlations spanning Chrons C29–C25. A similar improvement to correlations in Chron C24r has been incorporated from studies in DSDP Hole 550 (Berggren and Aubry, 1995). Second order, or inferred, (magnetobiostratigraphic) correlations are used where considered relevant and discussed at the appropriate place(s) in Tables 8 to 13. Additional background information on the historical development of Paleogene planktonic foraminiferal zonations can be found in Berggren and Miller (1988).

Paleocene Zonation.—The notation “P” used by Berggren and Miller (1988) to denote a series of subtropical-tropical zones applicable on a global (exclusive of high southern and northern latitudes) is maintained here. However, several modifications to the existing zonal scheme are made based on studies made since 1988 and with a view toward bringing the zonal terminology in line with suggested modifications being made in the revision to the International Guide to Stratigraphic Principles (Salvador, 1994). A comparison between the Paleocene zonation

OLIGOCENE TIME SCALE

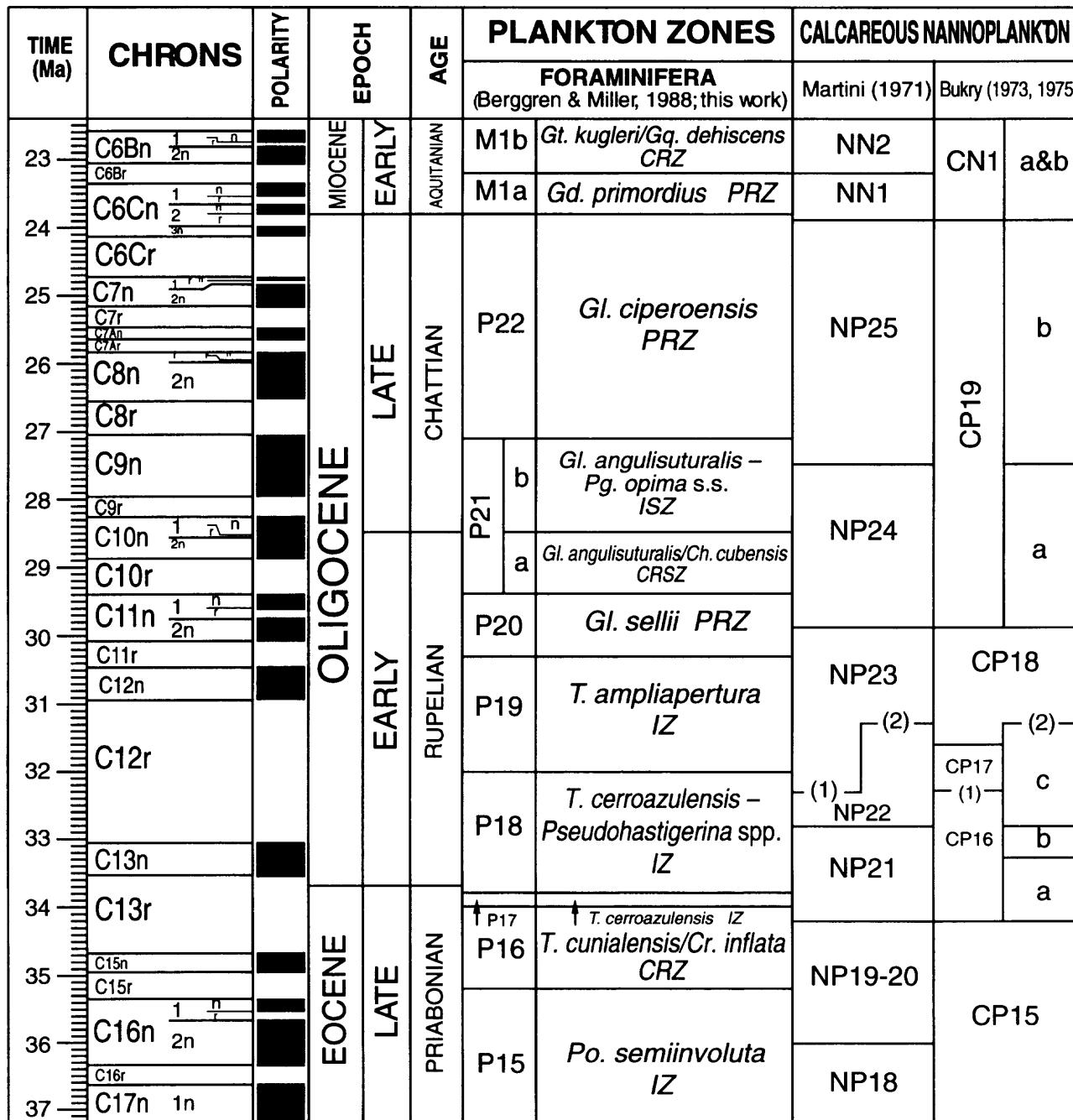


FIG. 3.—See Figure 1 for further explanation.

(re)defined in this paper and several earlier schemes is shown in Figure 7. The chronology of Paleocene planktonic foraminiferal datum events/zones is shown in Figure 8.

P0. *Guembelitria cretacea* Partial Range Zone (P0; Keller, 1988, emend. of Smit, 1982)

Definition: Biostratigraphic interval characterized by the partial range of the nominate taxon between the Last Appearance

Datum (LAD) of Cretaceous taxa (*Globotruncana*, *Rugoglobigerina*, *Globigerinelloides*, among others) at the K/P boundary as delineated by the essentially global iridium spike and the First Appearance Datum (FAD) of *Parvularugoglobigerina eugubina*.

Magnetostratigraphic calibration: Chron C29r (late part)

Estimated age: 65.0–64.97 Ma; earliest Paleocene (Danian)

EARLY MIocene TIME SCALE

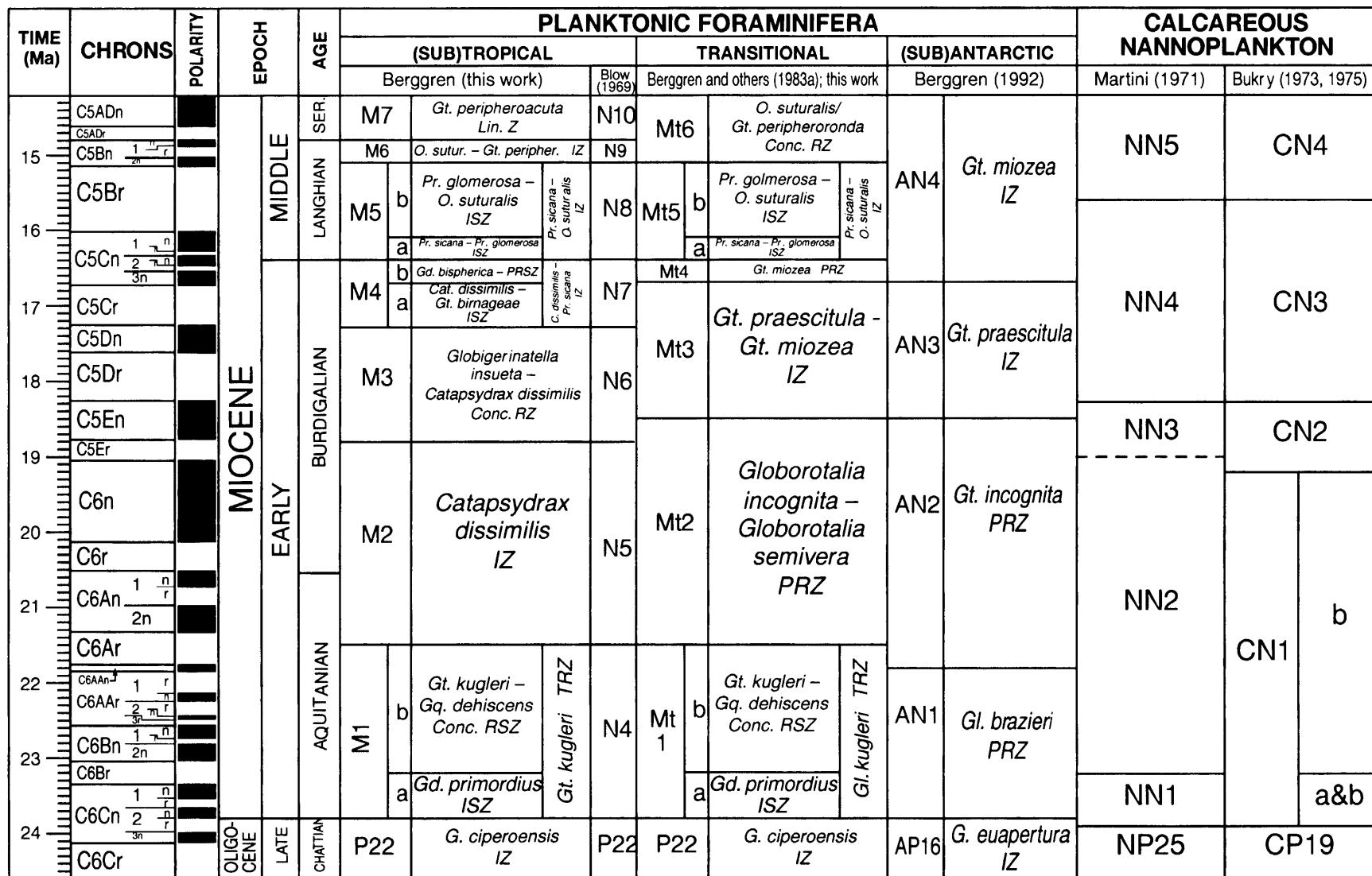


FIG. 4.—See Figure 1 for further explanation.

MIDDLE-LATE MIocene TIME SCALE

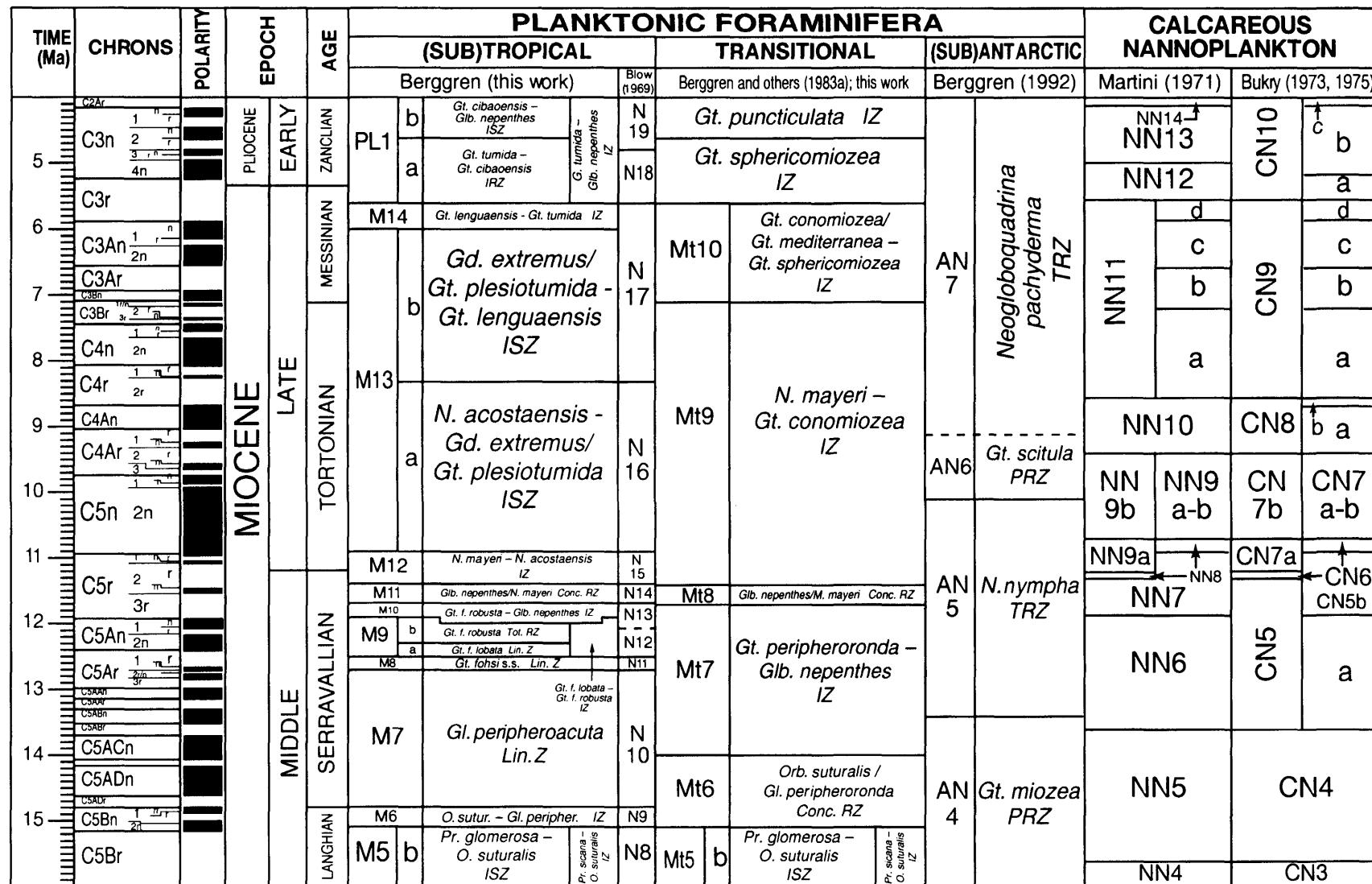


FIG. 5.—See Figure 1 for further explanation.

PLIOCENE-PLEISTOCENE TIME SCALE

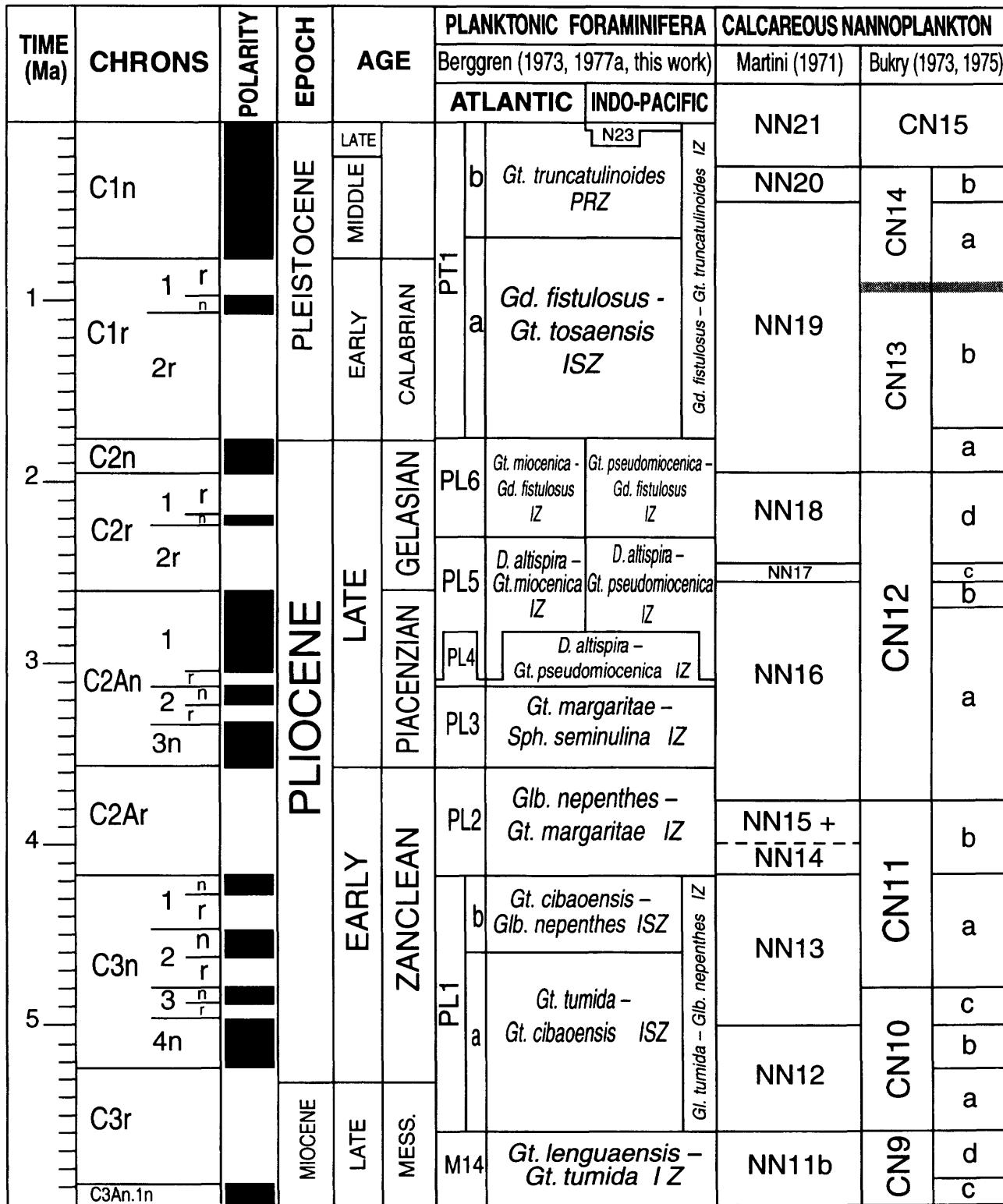


FIG. 6.—See Figure 1 for further explanation.

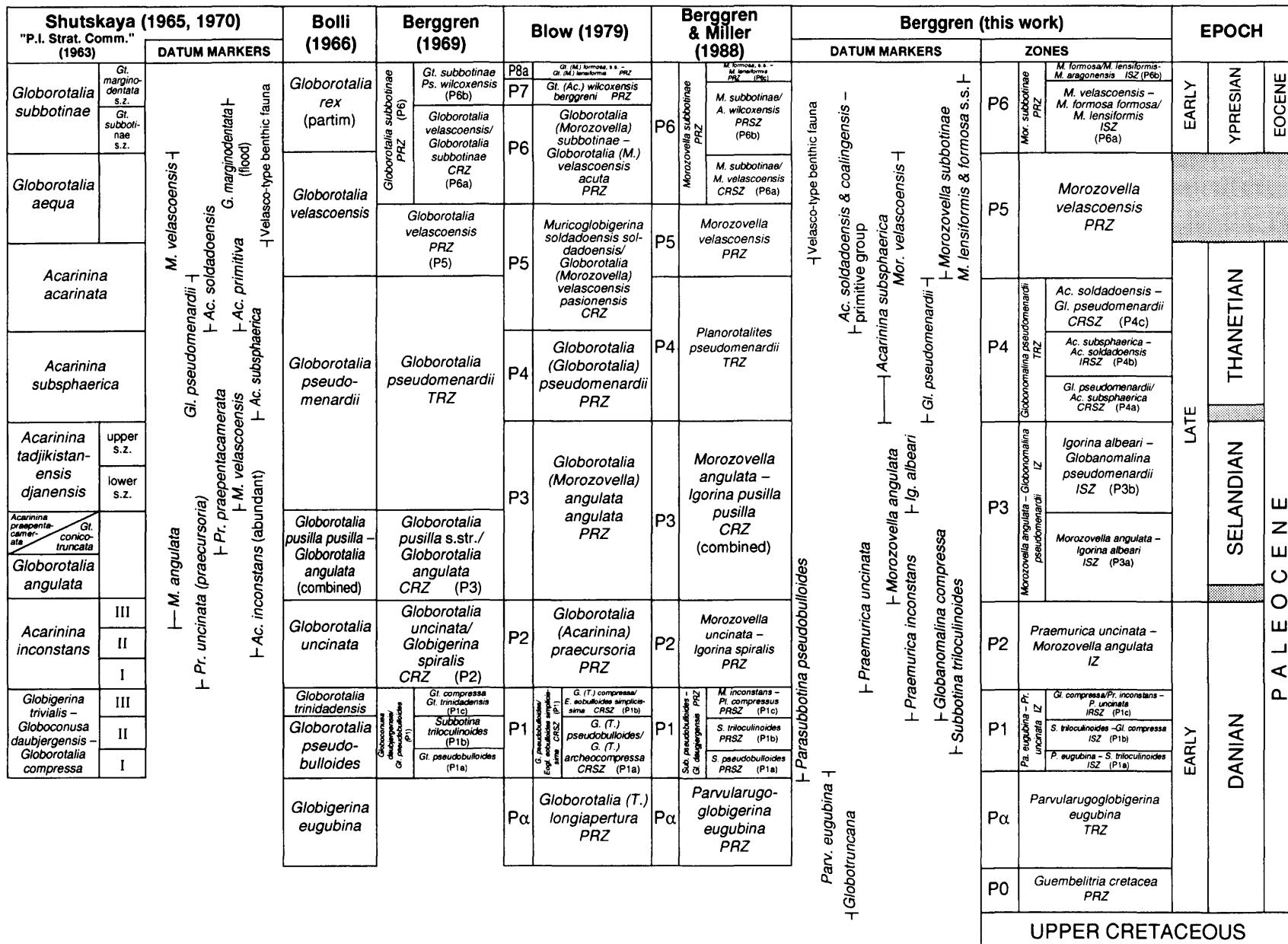


FIG. 7.—Comparison of Paleocene planktonic foraminiferal zonation (re)defined in this paper and several earlier schemes.

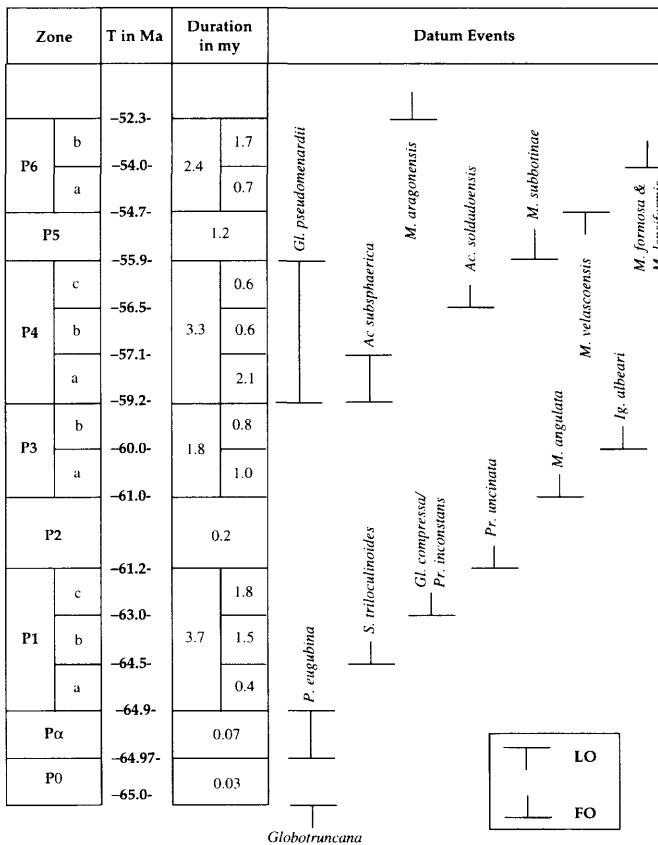


FIG. 8.—Chronology of Paleocene (sub)tropical planktonic foraminiferal zones.

Remarks: See below under *Parvularugoglobigerina eugubina* Total Range Zone.

Pa. *Parvularugoglobigerina eugubina* Total Range Zone (Liu, 1993, emend. of Pa of Blow, 1979; Luterbacher and Premoli Silva, 1964)

Definition: Biostratigraphic interval characterized by the total range of the nominate taxon

Magnetochronologic calibration: Chron C29r (later part)

Estimated age: 64.97–64.9 Ma; earliest Paleocene (Danian)

Remarks: The Cretaceous/Paleogene (K/P) boundary is located about two-thirds of the way up within Chron C29r with an assigned age of 65.0 Ma (CK92/95) vs. 66 Ma (CK92) and corresponds to the mass extinction of Cretaceous species of planktonic foraminifera at the recommended (and approved but currently contested) boundary stratotype at El Kef, Tunisia (Liu, 1993) and correlative levels elsewhere. The earliest Paleogene (Danian) planktonic foraminiferal Zones P0 and Pa (defined by the partial range of *Guembelitria cretacea* following the extinction of Cretaceous taxa at the K/P boundary and the initial appearance of *P. eugubina*, respectively; Keller, 1988, emend., Smit, 1982), now appear to be well recognized, although Zone P0 appears to be restricted to nearshore, rather than open ocean, environments and to be of extremely short duration. In view of the less equivocal taxonomic problems associated with the recognition of *P. eugubina* vs. the earliest representatives of *Parasubbotina pseudobulloides*, we follow Liu (1993) in recognizing

the terminal occurrence of the former rather than the initial appearance of the latter in defining the boundary between Zones Pa and P1.

Estimation of the age and duration of Zones P0 and Pa remains fraught with difficulty. Liu (1993) has pointed to the hazard of assuming constant rates of sedimentation across the K/P boundary in estimating biochronological datums owing to fluctuating (predominantly declining) productivity across (and particularly above) the boundary interval. He estimated a duration for the K/P boundary interval (i.e., the stratigraphic interval between the extinction of the Cretaceous taxa and the initial appearance of Paleogene eoglobigerinids in the assumedly continuously deposited section at Miller's Ferry, Alabama) of ~3.53 ky and 3.34 ky based on data in BKF85 (South Atlantic) and Groot and others (1989; Agost, Spain), respectively. He did this by using the estimated ages for the LAD of *P. eugubina* and the FAD of *Pa. pseudobulloides* in these two studies as calibration points. The FAD of *P. eugubina* was estimated to have occurred ~50 ky and 20 ky after the K/P boundary by BKF85 and Groot and others (1989), respectively. However, it should be borne in mind that the duration of Chron C29r is significantly different in BKF85 (570 ky) vs CK92 (869 ky) or CK92/95 (833 ky), and that the duration of the stratigraphic interval from the K/P boundary to the Chron C29n/r boundary is correspondingly lengthened and then shortened from 230 ky (BKF85) to 268 ky (CK92) to 255 ky (CK92/95). This difference simply has the effect of extending the duration of Zone P0 by about 30–35%. The duration of Zone Pa is also uncertain in view of conflicting data which suggest: a) biostatigraphic exclusion of the ranges of *P. eugubina* and *Pa. pseudobulloides* in the later part of Chron C29r at Agost (Groot and others, 1989) and b) an overlap (37 cm) in the stratigraphic range of these two taxa at Miller's Ferry (Liu, 1993). Despite the taxonomic problems associated with the recognition of the earliest morphotypes of *Pa. pseudobulloides* (Olsson and others, 1992) mentioned above, it would appear that most specialists agree that the FAD of *Pa. pseudobulloides* and the LAD of *P. eugubina* are closely associated (Poore and others, 1984; Liu, 1993; see also Blow, 1979), and that these two events occur within the later part of Chron C29r, somewhat older than that estimated in BKF85. We take a compromise view here between the data in Poore and others (1984), Groot and others (1989) and Liu (1993) in viewing the FAD of *P. eugubina* in the later part of Chron C29r (Poore and others, 1984; Groot and others, 1989) with an estimated calibration of 66.43 Ma (by Groot and others, 1989) as definitive; a revised age of 64.97 Ma is suggested here based on calibration to CK92/95. With regard to the upper limit of *eugubina*, we view the overlap in the ranges of *eugubina* and *pseudobulloides* as real (Blow, 1979; Poore and others, 1984; Liu, 1993; pers. observ., WAB) and place the Pa/P1 zonal boundary just below the Chron C29n/r boundary, at (admittedly somewhat arbitrarily) 64.8 Ma (CK92/95). The P0 and Pa Zones would then have estimated durations of 30 ky and 170 ky, respectively. The difference between Liu's (1990) estimate of ~3-ky duration for Zone P0 vs our estimate of 30 ky illustrate the difficulty and uncertainty in estimating durations of the earliest Paleocene Biozones.

P1. *Parvularugoglobigerina eugubina-Praemurica uncinata* Interval Zone (P1; defined herein; emend. of Berggren and Miller, 1988).

Definition: Biostratigraphic interval between the LAD of *Parvularugoglobigerina eugubina* and the FAD of *Praemurica uncinata*.

Magnetostratigraphic calibration: Chron C29r (later part)-Chron C27n(0)

Estimated age: 64.9–61.2 Ma; early Paleocene (Danian)

Remarks: Zone P1 (the biostratigraphic interval between the LAD of *P. eugubina* and the FAD of *Pr. uncinata*) has been subdivided into three subzones based on the sequential appearances of *Subbotina triloculinoides* and *Globanomalina compressa/Pr. inconstans* (Berggren and Miller, 1988). The FAD of *S. triloculinoides* (=P1a/b) occurs in the early to mid-part of Chron C29n at DSDP Hole 384 with an estimated age of 64.5 Ma and that of *Gl. compressa* (=P1b/c) in mid-Chron C28n in Hole 384 (63.0 Ma, Table 8). The zone as redefined here is essentially the same as Zone P1 in Berggren and Miller (1988), except that the LAD of *P. eugubina*, rather than the FAD of *Pa. pseudobulloides*, has been adopted to characterize the base of the zone (following Liu, 1993). Definition as an interval zone allows its recognition in a relatively unequivocal manner.

P1a. *Parvularugoglobigerina eugubina*-*Subbotina triloculinoides* Interval Subzone (P1a; herein defined; emendation of *Pa. pseudobulloides* Subzone (P1a) in Berggren and Miller, 1988)

Definition: Biostratigraphic interval between the LAD of *Parvularugoglobigerina eugubina* and the FAD of *Subbotina triloculinoides*

Magnetostratigraphic calibration: Chron C29r (later part)-Chron C29n (mid part)

Estimated age: 64.9–64.5 Ma; early Paleocene (early Danian)

Remarks: The biochronologic denotation of this subzone is virtually the same as that of Subzone P1a in Berggren and Miller (1988), but the biostratigraphic connotation has been emended to the extent that the LAD of *P. eugubina*, rather than the FAD of *Pa. pseudobulloides*, has been used as the criterion for the definition of its base following Liu (1993). Characteristic elements of this subzone include: spinose eoglobigerinids (*Eoglobigerina eobulloides*, *E. edita*), parasubbotinids (*Pa. pseudobulloides*), non spinose praemorozovellids (*Pr. pseudoinconstans*, *Pr. taurica*) and globanomalinids (*Gl. archaeocompressa*, *Gl. planocompressa*) and *Globoconusa daubjergensis*.

P1b. *Subbotina triloculinoides*-*Globanomalina compressa*/*Praemurica inconstans* Interval Subzone (P1b; herein defined; emendation of, but equivalent to, Subzone P1b in Berggren and Miller, 1988)

Definition: Biostratigraphic interval between the FAD of *Subbotina triloculinoides* and the FADs of *Globanomalina compressa* and/or *Praemurica inconstans*

Magnetostratigraphic calibration: Chron C29n (mid part)-Chron C28n (mid part)

Estimated age: 64.5–63.0 Ma

Remarks: This subzone has the same biochronologic denotation as Subzone P1b in Berggren and Miller (1988) but its biostratigraphic connotation is emended to the extent that it is defined here as an interval subzone rather than as a partial range subzone of the taxon *S. triloculinoides*. *Pa. varianta* has its FAD within this biostratigraphic interval, although it does not become a significant and morphologically distinct element in Paleocene faunas until Zone P3.

P1c. *Globanomalina compressa*/*Praemurica inconstans*-*Praemurica uncinata* Interval Subzone (P1c; herein defined; emendation of, but equivalent to, Subzone P1c in Berggren and Miller, 1988).

Definition: Biostratigraphic interval between the FAD of *Globanomalina compressa* and/or *Praemurica inconstans* and the FAD of *Praemurica uncinata*

Magnetostratigraphic calibration: Chron C28n (mid)-Chron C27n(o)

Estimated age: 63.0–61.2 Ma

Remarks: Our recent studies (Berggren and Norris, unpubl. data) do not support Blow's (1979, p. 944) suggestion of the synonymy of *Pr. uncinata* (Bolli) and *Pr. praecursoria* (Morozova) (cf., Berggren and Miller, 1988, p. 368), but we would agree with the latter as to the synonymy between *Pr. inconstans* (Subbotina) and *Pr. trinidadensis* (Bolli). We regard *praecursoria* as an advanced morphotype of *inconstans*.

It should be noted that the FAD of *Pr. trinidadensis* was used as denotative of the P1b/c boundary in BKF85. The FADs of *inconstans* (*trinidadensis*) and *compressa* are virtually simultaneous in Chron C28n and are retained here as alternate definitive elements in recognizing this subzone.

P2. *Praemurica uncinata*-*Morozovella angulata* Interval Zone (P2; herein defined; emend. of, but biostratigraphically equivalent to, Zone P2 in Berggren and Miller, 1988)

Definition: Biostratigraphic interval between the FAD of *Praemurica uncinata* and the FAD of *Morozovella angulata*

Magnetostratigraphic calibration: Chron C27n(o)-Chron C27n(y)

Estimated age: 61.2–61.0 Ma; late early Paleocene (late Danian)

Remarks: Zone P2, as used here, has the same biostratigraphic extent but somewhat different taxonomic connotation; work by WAB and Richard Norris (WHOI) suggests that the taxa *praecursoria* and *uncinata* are not synonymous (cf. Berggren and Miller, 1988, p. 368) as suggested by Blow (1979, p. 944) but that *trinidadensis* and *inconstans* (as well as *praecursoria*) are conspecific (cf. Blow, 1979) and the taxon *uncinata* is retained here as the nominative taxon of Zone P2. In DSDP Hole 384, we have recently found (Berggren and others, 1994) that the range of *Pr. uncinata* effectively brackets Chron C27n (Table 8). At Hole 577, the transition from *Pr. inconstans-trinidadensis* to *Pr. uncinata* occurs in the upper part of Core 12 and in a reversed interval immediately above Chron C28n which, by correlation, is close to Chron C27n in the adjacent Hole 577A; a brief hiatus is suspected to occur at this level in Hole 577 (see also discussion, below, of the FAD of *Ellipsolithus macellus* in section on Calcareous Nannofossil Magnetostratigraphy: Paleogene). At any rate, the FAD of this taxon here is seen to be consistent with the earlier (BKF85) calibration to Chron C27n and correlation with Zone NP4 (Table 8, Item 24). However, that was based primarily on calibration in the northern Apennines based on thin-section analysis. The more precise determination provided here is based on well preserved material in deep-sea cores. In DSDP Hole 384, *Pr. uncinata* has its FAD (and can be seen to evolve from *Pr. inconstans*) at the base of Chron C27n at the same level as the FAD of (the muricate but non-carinate) *M. praeangulata* in Zone NP4 which is believed to lie at the base of the morozovellid radiation. It has its FAD at a comparable level in ODP Hole 758A (Indian

TABLE 8.—RELATIONSHIP OF PALEOCENE PLANKTONIC FORAMINIFERAL DATUM LEVELS TO OBSERVED (AND INTERPRETED) MAGNETIC POLARITY STRATIGRAPHY. AGE ESTIMATES (MA) DERIVED FROM THE GPTS OF CANDE AND KENT (1992/1995) AND ADOPTED IN THIS PAPER. INFERRRED ESTIMATES (I.E., WHERE DIRECT MAGNETOBIOCHRONOLOGIC CALIBRATION IS LACKING) ARE PRESENTED IN PARENTHESIS. THESE DATA HAVE PROVIDED THE BASIC MAGNETOBIOCHRONOLOGIC FRAMEWORK FOR ESTIMATING THE CHRONOLOGY OF STANDARD TIME-STRATIGRAPHIC UNITS AND STAGE STRATOTYPES.

PALEOCENE

Datum	FAD	LAD	Paleomagnetic Chron	Age in Ma	Reference	Remarks
1. <i>Morozovella acuta</i>		X	C24r	54.7	1	Occurs midway between -17 (54.5 Ma) and + 19 (54.0 Ma) Ash Beds in Hole 550 and taken as proxy for the P5/P6 a zonal boundary there.
2. <i>Morozovella velascoensis</i>		X	C24r	54.7	2	P6a/b boundary in Berggren and Miller (1988); Zone P5/P6 boundary in this paper; generally used to approximate the Paleocene/Eocene boundary.
3. <i>Globanomalina australiformis</i>	X		C24r	55.5	3	Holes 689B, 690B; used to denote the P/E boundary in high southern latitudes (ref. 3).
4. <i>Morozovella subbotiniae</i>	X		C25n _(y)	55.9	4,5	Hole 577.
5. <i>Globanomalina pseudomenardii</i>		X	C25n _(y)	55.9	1,4-6	P4/P5 boundary. Recorded in base C24r (ref. 4) and top C25n (ref. 5) in Hole 577 and top C25n in Hole 752 (ref. 6). Juxtaposition/overlap of <i>Gl. pseudomenardii</i> LAD and <i>M. subbotiniae</i> FAD observed in Holes 465 and 758 (ref. 7).
6. <i>Acarinina acarinata</i>		X	C25r	56.3	1	Hole 384; at comparable levels (without paleomagnetic control) in Holes 465 and 758A (ref. 1).
7. <i>Acarinina mckannai</i>		X	C25r	56.3	1	Hole 384; at comparable levels (without paleomagnetic control) in Holes 465 and 758A (ref. 1).
8. <i>Morozovella aqua</i>	X		C25r	56.5	1	Holes 384 (N. Atlantic), 465 (Ontong-Java Plateau, equatorial Pacific), 758A (Indian Ocean) in association with FAD of <i>Acarinina coalingensis-triplex</i> group and <i>Ac. soldadoensis</i> (see below).
9. <i>Acarinina coalingensis—triplex</i>	X		C25r	56.5	1	Hole 384; at comparable levels (without paleomagnetic control) in Holes 465 and 758A (ref. 1).
10. <i>Acarinina soldadoensis</i>	X		C25r	56.5	1	P4 b/c boundary (this paper). Hole 384; at comparable levels (without paleomagnetic control) in Holes 465 and 758A (ref. 1).
11. <i>Acarinina subsphaerica</i>		X	C26r	57.1	1	P4 ab boundary (this paper). Hole 384; at comparable levels (without paleomagnetic control) in Holes 465 and 758A (ref. 1). The LAD of this taxon occurs approximately mid-way in Zone P4.
12. <i>Acarinina mckannai</i>	X		C26r	59.1	1	Hole 384; at comparable levels (without paleomagnetic control) in Holes 465 and 758A (ref. 1).
13. <i>Acarinina subsphaerica</i>	X		C26r	59.2	1	Hole 384; at comparable levels (without paleomagnetic control) in Holes 465 and 758A (ref. 1).
14. <i>Acarinina acarinata</i>	X		C26r	59.2	6	Hole 384; at comparable levels (without paleomagnetic control) in Holes 465 and 758A (ref. 1) The FAD of three acarininids (i.e., <i>acarinata</i> , <i>subsphaerica</i> , <i>mckannai</i>) has been observed to coincide closely with the FAD of <i>Gl. pseudomenardii</i> (this paper).
15. <i>Globanomalina pseudomenardii</i>	X		C26r	59.2	2,5	Hole 384; at comparable levels (without paleomagnetic control) in Holes 465 and 758A (ref. 1) Younger part of C26r in Hole 577 (ref. 4) within Zones CP5-CP6 (undiff.); FAD recorded in C25r in Zone CP5 (=NP6) in Hole 605 (ref. 8) but in C26n in CP5 (=P5) in Hole 605 in refs. 8, 9; see also ref. 2.
16. <i>Parasubbotina varianta</i>		X	C26r	59.2	1	See under 17 below.
17. <i>Parasubbotina variolaria</i>		X	C26r	59.2	1	<i>P. variolaria</i> and <i>P. varianta</i> have simultaneous LADs in Holes 465 and 384.
18. <i>Morozovella velascoensis</i>	X		C26r	60.0	1,2	Hole 384; at comparable levels (without paleomagnetic control) in Holes 465 and 758A (ref. 1).
19. <i>Muricella albeari</i> (= <i>M. laevigata</i>)	X		C26r	60.0	1	P3a/b subzonal boundary of this paper (not P3a/b subzonal boundary in Berggren and Miller, 1988); occurs approximately mid-way in Zone P3 in Holes 463 and 758A and in the mid-part of C26r in Hole 384.
20. <i>Praemurica strabocella</i>	X		C26r	60.5	1	Occurs in Holes 384 and 758A midway between FAD <i>M. angulata</i> and FAD <i>M. albeari</i> and in Zone NP5; recorded in Hole 690 in lower Zone CP5 (=NP6, ref. 2); in Hole 689B at level in Zone CP8 (=NP9) but equated with C26n (ref. 2); recorded in Hole 738 at CP4 /CP5 (=NP5/N P6) zonal boundary (ref. 10).
21. <i>Morozovella conicotruncata</i>	X		C26r (early part)	60.9	1	Occurs at virtually the same level as FAD <i>M. angulata</i> in Holes 384, 465, 758A (ref. 1) and 577 (refs. 6,7). Definite position in Hole 577 difficult to determine because of absence of C27n (Bleil, 1985).
22. <i>Muricella pusilla</i>	X		C26r	61.0	1,5	Occurs in early C26r and top Zone CP3 (=NP3) in Hole 577 (refs. 4, 5) but precise position difficult to determine because of absence of C27n and possible unconformity just above C28n at 102.95 m (see Bleil, 1985, p. 449–450). Occurs at some level as FAD of <i>M. angulata</i> and <i>M. conicotruncata</i> in Holes 465 and 758A (ref. 1).
23. <i>Morozovella angulata</i>	X		C27n _(y)	61.0	1,2	In Hole 577 occurs in early C26r (ref. 1, 5), (but precise position difficult to determine because of absence of C27n (Bleil, 1985); in Hole 384 it occurs <2-m above FAD of <i>P. uncinata</i> in NP4 and C27n _(y) , 2-m above FAD <i>P. uncinata</i> in Holes 465 and 758A (ref. 1).
24. <i>Praemurica uncinata</i>	X		C27n _(o)	61.2	2	The FAD of <i>P. uncinata</i> occurs in Hole 577 (refs. 1, 5) just above a N-R polarity reversal (C28n); C27n is missing in Hole 577 (Bleil, 1985, p. 446, Fig. 5, p. 449, Fig 7B) and there may be a short hiatus at/near the level if FAD of this taxon in C27n (ref. 2) is correct; alternatively C27n may be missing in the core break between Cores 11 and 12 (~101.8 m) in which case the FAD of this taxon would be near the C27r/C28n boundary (see ref. 2); in Hole 384 it occurs at the same level as FAD <i>M. praearangulata</i> in Zone NP4 (ref. 1) at the base of C27n, as well as in Holes 465 and 758A (ref. 1).
25. <i>Morozovella praearangulata</i>	X		C27n _(o)	61.2	1	Hole 384; at comparable levels (without paleomagnetic control) in Holes 465 and 758A (ref. 1); see remarks above (item 23).
26. <i>Globanomalina imitata</i>	X		(?C2 7n _(o))	(61.3)	3	Holes 689B, 690B (ref. 3).
27. <i>Praemurica inconstans</i>	X		C28n(mi d)	63.0	3	Holes 689B, 690C (ref. 3) and 384 (ref. 1)

TABLE 8.—Continued.
PALEOCENE

Datum	FAD	LAD	Paleomagnetic Chron	Age in Ma	Reference	Remarks
28. <i>Globanomalina compressa</i>	X		C28n(mid)	63.0	1,2	Hole 384 (ref. 1); also occurs at comparable level (by correlation) in Hole 750A in interval with no polarity data just above incomplete C28n in 750A/14/2:44 to 750A/14/2:40 (ref. 6; see also ref. 1).
29. <i>Parasubbotina varianta</i>	X		C28n(mid)	63.0	1	Hole 384, mid-Zone NP2 (ref. 1) and at comparable level by correlation in Hole 750A.
30. <i>Parvularugoglobigerina eu-gubina</i>	X		C29r	64.7	1,3,10,11	Hole 738 (ref. 10), Hole 384 (ref. 1) and Agost, Spain (ref. 11); first common occurrence (FC O) noted at C29n _(o) in Holes 689, 690 (ref. 2).
31. <i>Subbotina triloculinoides</i>	X		C29n	64.3	1	Hole 384 (ref. 1).
32. <i>Parvularugoglobigerina eu-gubina</i>	X		C29r	64.97	11	Agost, Spain (ref. 11; see discussion in text).
33. <i>Globotruncana</i>	X		C29r	65.00	12	

¹this work²Berggren and others, 1985b³Stott and Kennett, 1990⁴Corfield, 1987⁵Liu and Olsson (pers. commun., 1993)⁶Pospichal and others, 1991⁷Nederbragt and van Hinte, 1987⁸Saint Marc, 1987⁹Moullade, 1987¹⁰Huber, 1991¹¹Groot and others, 1989¹²multiple sources

Ocean). In ODP Holes 738 and 750A the FAD of *M. praeangulata* occurs at apparently the same stratigraphic level (within Zone NP4) and in Hole 750A this occurs near the base of Core 11 within an interval of no magnetostratigraphy slightly above a short (and incomplete) normal event identified here (and in Schlich and others, 1989, p. 308) as Chron C27n. However, reference to the Initial Reports of Site 750 (Schlich and others, 1989, p. 308, 576) reveals that there is an approximately 7-m coring gap (no recovery) between the lowest occurrence of *M. praeangulata* (base Core 11 at ~310 m) and the top of Core 12 at ~317 m (where the (incomplete) top of Chronozone C27n occurs). Thus, the incomplete record in the southern Indian Ocean supports the FAD of *M. praeangulata* (=FAD of *Pr. uncinata*) at least as early as the younger part of Chron C27n as recorded earlier in BKF85 (p. 189). Further, but inconclusive, data come from Hole 577 where the FAD of *Pr. uncinata* occurs just above Chron C28n, but Chron C27n is absent at this location because of an unconformity at the break between Cores 11 and 12 at ~101.87 m (see Bleil, 1985, and section on Calcareous Nannofossil Magnetobiochronology: Paleogene, Table 14) thus making it difficult to determine whether the reversed interval above Chron C28n is Chron C27r or C26r. The relatively thin stratigraphic interval of Zone P2 (~2–3 m at several deep-sea sites) supports the relatively short temporal interval estimated for this zone. For example in DSDP Hole 384, the FAD of *Pr. uncinata* (150.75 m), *M. angulata* (148.70 m), and *M. conicotruncata* (146.3 m) over a 3-m interval attests to the short temporal span of Zone P2 (see BKF85) and the very rapid branching of the morozovellid lineage between about 61–60 Ma.

P3. *Morozovella angulata-Globanomalina pseudomenardii* Interval Zone (P3, herein defined; emendation of Zone P3 in Berggren and Miller, 1988).

Definition: Biostratigraphic interval between the FAD of *Praemurica angulata* and the FAD of *Globanomalina pseudomenardii*

Magnetostratigraphic calibration: Chron C27n(y)-Chron C26r (mid)

Estimated age: 61.0–59.2 Ma; late Paleocene (Selandian)

Remarks: Zone P3 is the biostratigraphic interval between the FAD of *M. angulata* and that of *Globanomalina pseudomenardii* (Berggren and Miller, 1988, p. 368). It has been subdivided into a lower (a) and an upper (b) subzone based on the (presumed) FAD of *Igorina pusilla* in the lower third of the biostratigraphic interval. However our recent studies on DSDP Holes 384, 465 and ODP Hole 758A have shown clearly that the FAD of *pusilla* coincides with that of *M. angulata* and *M. conicotruncata* at the base of Zone P3 (see also Blow, 1979: 1109) but that the FAD of its descendant form *Ig. albeari* (= *Ig. pusilla laevigata*) occurs about midway within Zone P3 and this occurrence has been used to define a new subdivision of Zone P3 (Berggren and Norris, 1993).

P3a. *Morozovella angulata-Igorina albeari* Interval Subzone (P3a; herein defined)

Definition: Biostratigraphic interval between FAD of *Morozovella angulata* and FAD of *Igorina albeari*

Magnetostratigraphic calibration: Chron C27n(y)-Chron C26r (early)

Estimated age: 61.0–60.0 Ma; early late Paleocene (Selandian)

Remarks: We have chosen to use *M. angulata* as the denominative form for the base of this subzone because of the rarity or sporadic occurrence (in some cases) of *Ig. pusilla* in the lower part of this subzone. Indeed, the FAD of *Ig. pusilla* has been clearly observed to occur together with the FAD of *M. angulata* and *M. conicotruncata* (at the base of Zone P3) in DSDP/ODP Holes 465 and 758A.

P3b. *Igorina albeari-Globanomalina pseudomenardii* Interval Subzone (P3b; herein defined)

Definition: Biostratigraphic interval between FAD of *Igorina albeari* and the FAD of *Globanomalina pseudomenardii*

Magnetostratigraphic calibration: Chron C26r (early)-Chron C26r (mid)

Estimated age: 60.0–59.2 Ma; late Paleocene (Selandian)

Remarks: The FAD of the weakly but densely muricate, keeled *Igorina albeari* is a distinct biostratigraphic datum event that is clearly seen about midway in the biostratigraphic interval between the FAD of *M. angulata* and the FAD of *Gl. pseudo-*

menardii. It occurs a short distance just below (brief time interval before) the FAD of *M. velascoensis* from its ancestor *M. conicotruncata*. A distinctive feature of the upper part of this (sub)zone is the common occurrence of large, robust representatives of *Pa. varianta* and (in some areas) of the large, robust, and uniquely umbilically-toothed *Pa. variolaria*; both these taxa have their LAD near the P3/P4 zonal boundary.

P4. *Globanomalina pseudomenardii* Total Range Zone (P4; Bolli, 1957a)

Definition: Biostratigraphic interval of the total range of the nominate taxon, *Globanomalina pseudomenardii*

Magnetostratigraphic calibration: Chron C26r (mid)-Chron C25n(y)

Estimated age: 59.2–55.9 Ma; middle part of late Paleocene (late Selanian-Thanetian)

Remarks: Zone P4 is the biostratigraphic interval characterized by the total range of the nominate taxon, *Gl. pseudomenardii* (Berggren and Miller, 1988, p. 370). The FAD of this taxon has been recorded in Chron C26n and in Zone CP4 (=NP5) by Moullade (1987) but in Chron C25r and in Zone CP5 (=NP6) by Nederbragt and van Hinte (1987) in DSDP Hole 605. However, the calcareous nannoplankton magnetostratigraphic correlations of Lang and Wise (1987) in Hole 605 differ significantly (by about 1/2 a chron and >1 my) from those indicated in BKF85. The anomalously young “FAD” of *Gl. pseudomenardii* and nannoplankton “datum events” at Site 605 may be due to generally poor preservation at this location. In DSDP Hole 577, the FAD of this taxon occurs in the younger part of Chron C26r in Zone CP5–6 (undifferentiated; =NP5–6; Table 8). In DSDP Hole 384, we have recently found that the FAD of *Gl. pseudomenardii* occurs in mid-Chron C26r with an estimated age of 59.2 Ma (Berggren and others, 1994).

The upper limit of Zone P4 has been the subject of considerable debate (see discussion in Berggren and Miller, 1988, p. 370). The succeeding Zone P5 (of Berggren and Miller, 1988, p. 370) has been defined as the partial range of *M. velascoensis* between the LAD of *Gl. pseudomenardii* and the FAD of *M. subbotinae*. In BKF85 this interval was shown to be of relatively short duration (~0.5 my). However, recent studies at DSDP Site 577 (Corfield, 1987; Liu and Olsson, pers. commun. 1992) show a juxtaposition of these two biostratigraphic events in the early part of Chron C24r in the case of the former and at the top of Chron C25n in the case of the latter. A similar juxtaposition/overlap has been observed in DSDP/ODP Holes 465 and 758A (WAB). In DSDP Hole 550 (NE Atlantic) the lowest occurrence of *M. subbotinae* is near the top of a dissolution interval which is itself ~8–13 m above the top of Chronozone C25n; thus its FAD, there, is a minimum/delayed occurrence, although it has not been observed in the dissolution free interval just above Chron C25n. In the stratigraphic sections Ermua and Trabakua of the deep-water Basque Basin (Western Pyrenees, Spain) Orue-Etxebarria and others (1992) record the simultaneous LAD of *Gl. pseudomenardii* and FAD of *M. subbotinae*, respectively. At Zumaya (Spain), Canudo and Molina (1992) recorded a short stratigraphic interval between these two biostratigraphic datums and indicate the presence of Zone P5, although they substitute a redefined *M. aequa* Zone for the biostratigraphic interval between the LAD of *Gl. pseudomenardii* and the FAD of *Pseudohastigerina wilcoxensis*, in the general

absence of *M. velascoensis* in the relatively shallow water Pyrenees sections.

Thus, on the basis of available data, it would appear that Zone P6 (as defined) succeeds directly Zone P4 under ideal conditions, but that Zone P5 (Berggren and Miller, 1988) exists under conditions of delayed entry of *M. subbotinae*. To avoid confusion caused by the contiguous FAD of *subbotinae* and LAD of *pseudomenardii*, Zone P5 is redefined here to conform with earlier usage (see below).

We find it useful to subdivide Zone P4 into three subzones based on the appearance and/or ranges of specific muricate acarininids which make their first appearance within this zone. This subdivision materially improves the biostratigraphic/biochronologic resolution within this relatively long (~2 my) zone.

P4a. *Globanomalina pseudomenardii/Acarinina subsphaerica* Concurrent Range Subzone (P4a; herein defined)

Definition: Biostratigraphic interval characterized by the concurrent range of the two nominate taxa between the FAD of *Globanomalina pseudomenardii* and the LAD of *Acarinina subsphaerica*

Magnetostratigraphic calibration: Chron C26r (mid)-Chron C25r (early)

Estimated age: 59.2–57.1 Ma; late Paleocene (latest Selanian-early Thanetian)

Remarks: The small, tightly coiled and high spired muricate form *Ac. subsphaerica* is a distinct component of lower P4 faunas and has its FAD essentially coincident with that of *Ac. acarinata* and *Gl. pseudomenardii*, nominate taxon of Zone P4, in DSDP/ODP Holes 384, 465 and 758A (Berggren and Norris, unpubl.; Table 8). Its range is relatively short and it has its LAD approximately midway through Zone P4. As such, it provides a useful means of differentiating the lower and upper parts of Zone P4. In its present denotation, this subzone corresponds closely to the *Ac. subsphaerica* Zone as used in the Kuban River section (northern Caucasus) which has served as the classic reference section for pre-Oligocene Paleogene planktonic foraminiferal zonation of the SW part of the former Soviet Union (as defined in the Permanent Interdepartmental Stratigraphic Commission for the Paleogene of the U.S.S.R., 1963). It was also used in a more extended sense in the northern Caucasus and Crimea (Shutskaya, 1953, 1956, 1960a, b, 1962; Alimarina, 1962, 1963; Leonov and Alimarina, 1961, 1964; and Morozova, 1960) as the biostratigraphic interval between the LAD of *Globorotalia angulata* and the FAD of *Globorotalia subbotinae* (which was considered to coincide approximately with that of *Nummulites planulatus*; see Yanshin, 1960: Table 1) and it should be borne in mind that this taxon was sometimes identified as *Acarinina spiralis* by some Russian authors (e.g., Leonov and Alimarina, 1961). These data pertain to an earlier era when detailed biostratigraphic data were unavailable owing to the broad spacing of samples. The significant fact is that we are returning here, and in the case of Subzone P4b (below) to a zonal system which was correct and appropriate in its essentials (if not details) over 30 years ago.

Characteristic elements of this subzone include *M. velascoensis*, *M. angulata-conicotruncata* complex (which has its LAD in this interval), *M. apanthesma*, *Ac. mackanni* (which has its FAD in this interval), *Ig. albeari*, and *S. triloculinoides*, *S. triangularis* and *S. velascoensis*.

P4b. *Acarinina subsphaerica-Acarinina soldadoensis* Interval Subzone (P4b; herein defined)

Definition: Biostratigraphic interval from the LAD of *Acarinina subsphaerica* to the FAD of *Acarinina soldadoensis*

Magnetostratigraphic calibration: Chron C25r (early)-Chron C25r (late)

Estimated age: 57.1–56.5 Ma; late Paleocene (Thanetian)

Remarks: As defined here this subzone corresponds essentially to the *Ac. acarinata* Zone of the northern Caucasus as codified by the “Soviet Stratigraphic Commission” in 1963 apparently for the biostratigraphic interval between the LAD of *Ac. subsphaerica* and the FAD of *Gr. aqua*. Our studies have shown that the FAD of *M. aqua* essentially coincides with that of *Ac. soldadoensis* and the *Ac. coalingensis-triplex* complex so that biostratigraphic usage similar, if not identical, to that employed over 30 years ago in the former Soviet Union is implied. In DSDP Hole 384, the FAD of *Ac. soldadoensis* (and the *Ac. coalingensis-triplex* plexus) occurs in late Chron C25r (Berggren and others, 1994; Table 8). Characteristic elements of this subzone include, i.al., *Ac. acarinata*, *Ac. mckannai*, *Gl. pseudomenardii*, *M. apanthesma*, *M. velascoensis*, *S. velascoensis* and *S. triangularis*.

P4c. *Acarinina soldadoensis-Globanomalina pseudomenardii* Concurrent range Subzone (P4c; herein defined)

Definition: Biostratigraphic interval containing the concurrent range of the nominate taxa from the FAD of *Acarinina soldadoensis* to the LAD of *Globanomalina pseudomenardii*

Magnetostratigraphic calibration: Chron C25r (late)-Chron C25n(y)

Estimated age: 56.5–55.9 Ma; late Paleocene (late Thanetian)

Remarks: Blow (1979, p. 267–269) used the concurrent range of *Ac. soldadoensis* (FAD at base) and *M. velascoensis* *pasionensis* (LAD at top) to denote his Zone P5. Our studies do not corroborate Blow’s (1979) upper limit of *pasionensis* prior to that of *velascoensis*, but his recognition of the LAD of *Ac. acarinata* and *Ac. mckannai* at the top of his Zone P5, essentially coincident with the FAD of *M. subbotinae*, agrees well with our own observations and suggests that Subzone P4c (herein defined) coincides closely, if not precisely, with Zone P5 of Blow (1979). On the other hand we have not observed indigenous occurrences of *Gl. pseudomenardii* together with *M. subbotinae*, other than their juxtaposition/brief overlap at the base of Zone P5 (= Subzone P6a of Berggren and Miller, 1988). For example in DSDP Site 213 (Indian Ocean), a typical Zone P5 fauna (with *M. velascoensis* and *M. subbotinae*) occurs for at least 8.56 m above basalt basement with no *Gl. pseudomenardii*. We believe that records of (sporadic) occurrences of *Gl. pseudomenardii* in Zone P5 are due to reworking or may include specimens referable to taxa other than *pseudomenardii* (*Gl. chapmani*, *Gl. australiformis*, *Gl. planoconica*, etc.).

P5. *Morozovella velascoensis* Interval Zone (P5; Bolli, 1957a; P5 and P6a of Berggren and Miller, 1988)

Definition: Biostratigraphic interval between the LAD of *Globanomalina pseudomenardii* and the LAD of *Morozovella velascoensis*

Magnetostratigraphic calibration: Chron C25n(y)-Chron C24r (mid)

Estimated age: 55.9–54.7 Ma; latest Paleocene-earliest Eocene (latest Thanetian-earliest Ypresian)

Remarks: Zone P5, with a different denotation (partial range of the nominate taxon between the LAD of *Gl. pseudomenardii* and the FAD of *M. subbotinae*) was defined (Berggren and Miller, 1988) before the evidence for the juxtaposition/overlap of these two datum events which were used to define the top of Zone P4 and the base of Zone P6a, respectively, became available (cf. Blow, 1979, p. 265–267), although we would disagree with Blow (1979) on the upper limit of *pseudomenardii* in his Zone P7 (= P6b of Berggren and Miller (1988); = P6a herein). However, in some instances the initial appearance of *M. subbotinae* was delayed by the widespread occurrence of one or more distinct dissolution events that span the lower part of magnetozone C24r and Zone P5. The chronology of such a zone is obviously very tenuous and approximate, but this estimate is based on an assessment of conditions observed in DSDP Hole 550 and other deep-sea sites as well as various outcrop sections in the North Caucasus and the Mediterranean region. For this reason we have decided to revert to the previously, relatively unequivocal, usage of Bolli (1957a) in which the sequential LADs of *pseudomenardii* and *velascoensis* are used to bracket the partial, terminal range of *velascoensis* and which characterize a distinct biostratigraphic interval which spans the Paleocene/Eocene boundary as currently recognized by at least some (bio)stratigraphers. As a result of this modification to Zone P5, Zone P6 of Berggren and Miller (1988) is also modified. Zone P5 essentially contains the concurrent range of *M. subbotinae* (FAD) and *M. velascoensis* (LAD), but it is defined as a partial range zone because the definition of the top of Zone P4 is defined as the LAD of *Gl. pseudomenardii*.

Characteristic features of this zone include a relatively distinct turnover in the planktonic foraminifera including the appearance of *M. marginodentata*, *M. formosa gracilis*, *Ig. broederupi*, *Ac. wilcoxensis*, *Turborotalia pseudoimitata* and the relatively common occurrence of strongly muricate large acarininids (*soldadoensis*, *coalingensis-triplex* group).

The Paleocene/Eocene boundary is usually correlated with the P5/P6 (= P6a/b of Berggren and Miller, 1988) zonal boundary by planktonic foraminiferal specialists and is estimated at 54.7 Ma here (see discussion under Radiosotopic Chronology and in Berggren and Aubry, 1995). Calcareous nannoplankton specialists usually consider the NP9/NP10 zonal boundary, estimated here at ~55 Ma, as denotative of this boundary. The base of the London Clay Formation (Oldhaven Bed = Hales Clay = base Eocene = Ypresian/Thanetian boundary) has been cross correlated to the ~17 Ash in DSDP Hole 550 and dated in NW Europe at 54.5 Ma (see discussion under Radioisotopic Chronology). However, we choose to use an age estimate of 54.8 Ma for the base of the London Clay Formation based on sedimentation rates in DSDP Hole 550, rather than the ~17 Ash date. The problems associated with the identification and delineation of events suitable for the determination of an appropriate Paleocene/Eocene boundary Global Stratotype Section and Point (GSSP) are currently being examined by IGCP Project 308 (Paleocene/Eocene Boundary Events in Time and Space) and have been discussed in greater detail elsewhere (Berggren and Aubry, 1995; Aubry and others, 1995).

Eocene Zonation.—The chronology of Eocene (sub)tropical planktonic foraminiferal datum events/zones is shown in Figure 9.

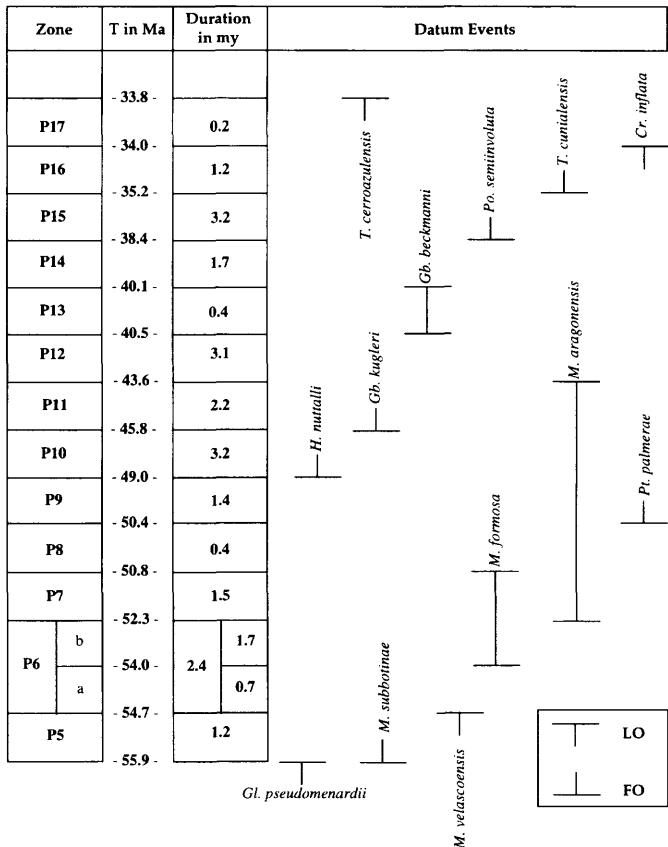


FIG. 9.—Chronology of Paleocene (sub)tropical planktonic foraminiferal zones.

P6. *Morozovella subbotinae* Partial Range Zone (P6 of Berggren and Miller, 1988, partim; herein emended and redefined; = *Morozovella subbotinae* Zone of Luterbacher and Premoli Silva in Caro and others, 1975, partim)

Definition: Biostratigraphic interval characterized by the partial range of the nominate taxon between the LAD of *Morozovella velascoensis* and the FAD of *Morozovella aragonensis*.

Magnetochronologic calibration: Chron C24r (mid)-Chron C23r

Estimated age: 54.7–52.3 Ma; early Eocene (early Ypresian)

Remarks: Berggren and Miller (1988, p. 370) defined the *M. subbotinae* Partial Range Zone (P6) as the partial range of the nominate taxon between its supposed FAD and the FAD of *M. aragonensis*. Investigations on a number of deep-sea cores and outcrop sections have now shown that the FAD of *M. subbotinae* coincides essentially with the LAD of *Gl. pseudomenardii* and that the supposed gap between the LAD of *pseudomenardii* and the FAD of *subbotinae* is illusory, although the delayed entry of *subbotinae* is often caused by strong dissolution in some sections within Zone NP9 (cf., Molina and others, 1992). Thus Zones P5 and P6a, as defined by Berggren and Miller (1988), are essentially equivalent. As emended here, Zone P6 coincides essentially with the *M. subbotinae* Zone of Premoli Silva and Bolli (1973) and Luterbacher and Premoli Silva in Caro and others, (1975), except for the (apparently brief) temporal interval between the LAD of *M. velascoensis* and the

LAD of the small, enigmatic taxon *M. edgari* (Premoli Silva and Bolli, 1973) (?= *M. finchi* Blow, 1979) which was shown by Toumarkine and Luterbacher (1985, Figure 5, p. 100) to occur only slightly below the simultaneous FADs of *M. formosa formosa* and *M. lensiformis* (cf. Blow, 1979, Figs. 48, 50, in which the LAD of *M. finchi* is shown to occur at essentially the same level). The temporal span between the LAD of *M. velascoensis* and the FAD of *M. formosa formosa* is estimated here at ~0.8 my.

In order to maintain numerical and biostratigraphic continuity with the zonation of Berggren and Miller (1988), we redefine Zone P6 in such a manner that its two subzones, a and b, now correspond to Subzones P6b and P6c, respectively, of Berggren and Miller (1988, p. 371).

P6a. *Morozovella velascoensis*-*Morozovella formosa formosa* and/or *Morozovella lensiformis* Interval Zone (P6a; = P6b of Berggren and Miller, 1988; numerical notation herein emended; = *Gr. edgari* Zone of Premoli Silva and Bolli, 1973, partim)

Definition: Biostratigraphic interval between the LAD of *Morozovella velascoensis* and the simultaneous FAD of *Morozovella formosa formosa* and/or *Morozovella lensiformis*

Magnetochronologic calibration: Chron C24r (mid)-Chron C24r (late)

Estimated age: 54.7–54.0 Ma; earliest Eocene (earliest Ypresian)

Remarks: In normal open ocean stratigraphic successions, the sequence of FAD of *M. subbotinae*, LAD of *M. velascoensis/acuta*, FADs of *M. formosa formosa*/*M. lensiformis* and the FAD of *M. aragonensis* serve as a means of providing a discrete biostratigraphic subdivision of the uppermost Paleocene-lowermost Eocene Series (Berggren and Miller, 1988). The subdivision made there has been followed, with minor modifications, in this paper.

This subzone is redefined here as an interval subzone so as to avoid conceptual confusion/overlap with the use of *M. subbotinae* as a nominate form of both Zone P6 and Subzone P6a in its original definition (Berggren and Miller, 1988, p. 370, 371) and for Zones P6 and Subzone P6a (emended here). At the same time we remove *Ph. wilcoxensis* as one of the nominate forms of Subzone P6a (P6b of Berggren and Miller, 1988); this form appears under ideal conditions at the P5/P6 (= P6a/b boundary in Berggren and Miller, 1988) in fully tropical assemblages but has a demonstrably delayed entry in mid-high latitude regions within the P6b-P7 (= P6c-P7 of Berggren and Miller, 1988) biostratigraphic interval.

The LAD of *S. velascoensis* occurs within this zone and the common and widespread early Eocene taxon *S. patagonica* assumes its characteristic morphologic features in this subzone. Additional comments on this subzone (as P6b) are to be found in Berggren and Miller (1988, p. 371).

P6b. *Morozovella formosa formosa*-*Morozovella lensiformis*-*Morozovella aragonensis* Interval Zone (P6b; = P6c of Berggren and Miller, 1988; numerical notation herein emended; Blow, 1979, as Subzone P8a)

Definition: Biostratigraphic interval between the virtually simultaneous FADs of *Morozovella formosa formosa* and/or *Morozovella lensiformis* and the FAD of *Morozovella aragonensis*

Magnetostratigraphic calibration: Chron C24r (late)-Chron C23r

Estimated age: 54.0–52.3 Ma; early Eocene (early Ypresian)

Remarks: This is a biostratigraphically distinct interval (see also Premoli Silva and Bolli, 1973; Blow, 1979) characterized by the essentially simultaneous FADs of the *M. formosa formosa* and *M. lensiformis* and the LADs of *M. subbotinae* and *M. aequa*.

P7. *Morozovella aragonensis/M. formosa formosa* Concurrent Range Zone (P7; Blow, 1979, as Subzone P8b; see also Berggren and Miller, 1988, p. 371, as Zone P7; Berggren, 1969 as *G. formosa* Zone; Bolli, 1966, as *Globorotalia formosa* and *G. aragonensis* Zones (combined))

Definition: Concurrent range of the nominate taxa between the FAD of *Morozovella aragonensis* and the LAD of *Morozovella formosa formosa*

Magnetostratigraphic calibration: Chron C23r-Chron C23n(y)

Estimated age: 52.3–50.8 Ma; middle early Eocene (mid-Ypresian)

Remarks: See Berggren and Miller (1988: 371).

P8. *Morozovella aragonensis* Partial Range Zone (P8; Berggren, 1969; see also Berggren and Miller, 1988, p. 371)

Definition: Partial range of the nominate taxon between the LAD of *Morozovella formosa formosa* and the FAD of *Planorotalites palmerae*

Magnetostratigraphic calibration: Chron C23n(y)-Chron C22r (estimated)

Estimated age: 50.8–50.4 Ma; late early Eocene (late Ypresian)

Remarks: See Berggren and Miller (1988, p. 371).

P9. *Planorotalites palmerae-Hantkenina nuttalli* Interval Zone (P9 of Berggren and Miller, 1988; herein emended)

Definition: Biostratigraphic interval between the FAD of *Planorotalites palmerae* and the FAD of *Hantkenina nuttalli*

Magnetostratigraphic calibration: Chron C22r (estimated)-Chron C22n(y)

Estimated age: 50.4–49.0 Ma; late early Eocene (latest Ypresian)

Remarks: This zone was originally denoted as the partial range of *S. inaequispira* with the same boundary criteria as employed here. By redefining this as an interval range zone we have simply lifted the onerous burden placed upon *inaequispira* as the name bearer of this extremely complex and controversial biostratigraphic interval (see Berggren and Miller, 1988, p. 372, 373 for further discussion). Characteristic elements of this zone include *S. inaequispira*, *S. frontosa*, *Ac. bullbrookii*, *Ac. pentamerata*, *Ac. aspensis*, *Planorotalites palmerae* (lower part), *M. aragonensis*, *M. caucasica*, *Ph. wilcoxensis*, *Ph. sharkriverensis*, *Globigerinatheka senni* and, in the upper part, the stellate, lobulate clavigerinellids.

P10. *Hantkenina nuttalli* Interval Zone (P10 of Berggren and Miller, 1988, p. 373; = *Hantkenina aragonensis* Zone of Bolli, 1957c, emended by Stainforth and others, 1975, and renamed by Toumarkine, 1981)

Definition: Biostratigraphic interval characterized by the presence/partial range of the nominate taxon between its FAD and the FAD of *Globigerapsis kugleri*

Magnetostratigraphic calibration: Chron C22n(y)-Chron C20r (estimated)

Estimated age: 49.0–45.8 Ma; early middle Eocene (early Lutetian)

Remarks: Characteristic elements of this zone include, in addition to the nominate form and *H. mexicana* s.l., clavigerinellids, *S. griffinae*, *S. inaequispira*, and (the virtually planispiral, inflated) *S. bolivariana*, *M. spinulosa*, *M. aragonensis*, *Ac. aspensis*, *Ac. matthewsae*, *Ac. bullbrookii*, and the distinctive, multi-apertured *Globigerinoides*-homeomorph *Guembeliotrioides higginsi*

The muricate multiapertured *Truncorotaloides collactea* and *Tr. rohri* make their initial, tentative appearance within this zone as well.

P11. *Globigerapsis kugleri/Morozovella aragonensis* Concurrent Range Zone (herein defined; = Bolli, 1957c, 1966, (upper part only); Berggren, 1969; P11 of Berggren and Miller, 1988)

Definition: Biostratigraphic interval characterized by the concurrent range of the nominate taxa between the FAD of *Globigerapsis kugleri* and the LAD of *Morozovella aragonensis*

Magnetostratigraphic calibration: Chron C20r (estimated)-Chron C20n(o)

Estimated age: 45.8–43.6 Ma; middle Eocene (Lutetian)

Remarks: At the time of its introduction (Berggren, 1969) the *Globigerapsis kugleri* Zone (P11) was based on the partial range of *Gb. kugleri* between its FAD and the LAD of *M. aragonensis*. As thus defined it was an interval zone, then corresponding to Bolli's (1957c) zone of the same name. The latter zone was emended by Proto Decima and Bolli (1970) and renamed by Bolli (1972) the *Globigerinatheka subconglobata subconglobata* Zone based on interim taxonomic studies of the group of early globigerinathekids. Its identification as a concurrent range zone (as the biostratigraphic interval with the nominate taxon from the FAD of *Globigerinatheka mexicana mexicana* to the LAD of *M. aragonensis*; see redefinition by Stainforth and others, 1975; Toumarkine and Luterbacher, 1985) is puzzling inasmuch as this definition is that of an interval zone, not a concurrent range zone. Berggren and Miller (1988, p. 373) denominated this zone as the *Gb. kugleri-S. frontosa* Partial Range Zone (based on the concurrent partial ranges of the nominate taxa between the FAD of *Gb. kugleri* and the LAD of *M. aragonensis*). As thus defined it was a hybrid of an interval and a concurrent range zone. Blow (1979, p. 285, 286) used the concurrent ranges of *Gb. kugleri* and *S. frontosa boweri* from the FAD of the former to the LAD of the latter to define his Zone P11. He considered the LAD of *frontosa boweri* to coincide essentially with the LAD of *M. aragonensis*, but Berggren and Miller (1988, p. 373) pointed out that *frontosa* has been reported to range as high as levels correlative with Zone P14 in Chronozone C18 (BKF85, p. 190). In following Blow's (1979) intent in retaining the concept, and delineating the limits, of Zone P11, we redefine it here insofar as we use the LAD of *M. aragonensis* (rather than the LAD of *S. frontosa*) to define its upper limit (with Zone P12).

A significant turnover in planktonic faunas occurs at, or near, the P11/P12 zonal boundary including the LADs of *M. aragonensis*, *S. griffinae*, *Turborotalia praecentralis*, *Ac. matthewsae*, the *Ig. broedermannii* group and *Clavigerinella akersi*.

At/near the P10/P11 zonal boundary the FADs of *M. lehneri*, *Gb. kugleri*, *T. pomeroli* (= *T. centralis* s.l.) and the LAD of "Subbotina" *bolivariana* are characteristic features. See Berggren and Miller (1988, p. 373) for additional discussion of this zone.

P12. *Morozovella lehneri* Partial Range Zone (Bolli, 1957c, 1966, emended; Berggren, 1969; P11 of Berggren and Miller, 1988)

Definition: Biostratigraphic interval characterized by the presence/partial range of nominate taxon between the LAD of *Morozovella aragonensis* and the FAD of *Globigerapsis beckmanni*

Magnetostratigraphic calibration: Chron C20n(o)-Chron C18r

Estimated age: 43.6–40.5 Ma; middle Eocene (Lutetian-early Bartonian)

Remarks: This zone is characterized by the relatively common occurrence of the nominate form together with *M. spinulosa*, *M. coronata*, *Tr. rohri*, *Tr. topilensis* and the transition from the primitive (*mexicana*) to more advanced (*alabamensis*) hantkeninids. As originally defined by Bolli (1957; see also Toumarkine and Luterbacher, 1985) this is a partial range (not an interval) zone.

P13. *Globigerapsis beckmanni* Total Range Zone (Bolli, 1957c, 1966; Blow, 1979, as P13; Berggren, 1969; Berggren and Miller, 1988, as P13)

Definition: Total range of the nominate taxon

Magnetostratigraphic calibration: Chron C18r-Chron C18n(o)

Estimated age: 40.5–40.1 Ma; late middle Eocene (Bartonian)

Remarks: Low conical morozovellids (*coronata*, *lehneri*) exhibit a rapid reduction within, and eventual extinction near the top of, this zone and only *spinulosa* continues to the overlying Zone P14 where it has its LAD.

P14. *Truncorotaloides rohri*-*Morozovella spinulosa* Partial Range Zone (P14 of Berggren and Miller, 1988; see also Blow, 1979)

Definition: Concurrent partial ranges of the nominate taxa between the LAD of *Globigerapsis beckmanni* and the FAD of *Porticulasphaera semiinvoluta*

Magnetostratigraphic calibration: Chron C18n(o)-Chron C18n(y)

Estimated age: 40.1–38.4 Ma; late middle Eocene (late Bartonian)

Remarks: The convoluted history of this zone is explained in more detail in Blow (1979, p. 291) and Berggren and Miller (1988, p. 373).

P15. *Porticulasphaera semiinvoluta* Interval Zone (P15, herein defined; similar, to Zone P15 of Blow, 1979; P15 of Berggren and Miller, 1988 but with different denotation at top)

Definition: Biostratigraphic interval between the FAD of *Porticulasphaera semiinvoluta* and the FAD of *Turborotalia cunialensis*

Magnetostratigraphic calibration: Chron C18n(y)-Chron C15r(o)

Estimated age: 38.4–35.2 Ma; late middle to early late Eocene (late Bartonian to early Priabonian)

Remarks: We have chosen to modify the denotation of this zone from its usual sense by redefining the top of the zone using the FAD of the relatively common and morphologically distinct (carinate periphery) and GPTS calibrated *T. cunialensis*, rather than that of *Cribrohantkenina inflata*, a taxon which is less common (relative to *cunialensis*) in some (sub)tropical stratigraphies and whose FAD remains poorly calibrated to the GPTS (Table 9, item 8). Both events occur close together in time but appear to be separated by a short/brief stratigraphic/temporal interval originally defined (with a somewhat different denotation) as an interval zone by Bolli (1957c), Blow (1979, p. 292) emended it so that the base coincided with the FAD of the nominate taxon, rendering it an interval, not a partial range, zone. See Berggren and Miller (1988, p. 374) for further discussion of the history of this zone (with a slightly different denotation).

Dentoglobigerinids (*galavisi*, *pseudovenezuelana*, *tripartita*) subbotinids (*angiporoides*, *linaperta*, *hagni*, *eocena*), catapsydracids (*unicavus*, *dissimilis*, *cryptomphala*, *pera*), globigerapsids (*index*, *tropicalis*) and (cribro)hantkeninids characterize this zonal interval. The LAD of the nominate taxon occurs only slightly older (~0.3 my) than the base of this zone.

P16. *Turborotalia cunialensis*/*Cribrohantkenina inflata* Concurrent-Range Zone (P16, herein defined; non Blow, 1969, 1979; non P16 of Berggren, 1969, and Berggren and Miller, 1988)

Definition: Biostratigraphic interval characterized by the concurrent range of the nominate taxa between the FAD of *Turborotalia cunialensis* and the LAD of *Cribrohantkenina inflata*

Magnetostratigraphic calibration: Chron C15r(o)-Chron C13r(mid)

Estimated age: 35.2–34.0 Ma; late late Eocene (late late Priabonian)

Remarks: In modifying the earlier definition(s) of Zone P16 we have chosen to stress the concurrent ranges of two distinct latest Eocene taxa. The LAD of *Cr. inflata* occurs in mid-Chron C13r, approximately midway temporally between the LADs of *Globigerapsis index* (earlier) and the hantkeninids and the *Turborotalia cerroazulensis* group (later) in the younger part of Chron C13r at the top of the Eocene. Characteristic features of this zonal interval include, among others, development of the acutely peripheried *Turborotalia cunialensis* (at the base), the FAD of "Turborotalia" *ampliapertura* and *T. pseudoampliapertura*, and the LAD of *Globigerapsis index*. Additional details on the calibration of faunal events in this zone can be found in Berggren and Miller (1988, p. 374) and Berggren and others (1992).

P17. *Turborotalia cerroazulensis* Interval Zone (P17 of Berggren and Miller, 1988)

Definition: Biostratigraphic interval between the LAD of *Cribrohantkenina inflata* and the extinction of *Turborotalia cerroazulensis*/*Turborotalia cunialensis*

Magnetostratigraphic calibration: Chron C13r (mid)-Chron C13r (late)

Estimated age: 34.0–33.8 Ma; latest Eocene (latest Priabonian)

Remarks: We retain the LAD of the *cerroazulensis/cunialensis* group to denote the boundary between Zones P17 and

TABLE 9.—EOCENE PLANKTONIC FORAMINIFERAL MAGNETOBIOCHRONOLOGY.
EOCENE

Datum	FAD	LAD	Paleomagnetic Chron	Age in Ma	Reference	Remarks
1. <i>Hantkenina</i> spp.	X	C13r	33.7	1-4		Located just above LAD of <i>T. cerroazulensis cunialensis</i> and youngest of 3 normal "events" in C13r in Contessa Highway section (refs. 2, 3) and above normal "event" = C13n.2n at Massignano (ref. 4).
2. <i>Turborotalia cerroazulensis</i>	X	C13r	33.8	1-4		Associated with youngest of 3 normal "events" in C13r in Contessa Section (ref. 2, 3) and above normal "event" = C13n.2n at Massignano (ref. 4). It is not absolutely clear whether the LAD of <i>Hantkenina</i> and <i>T. cerroazulensis</i> group are synchronous or sequential. Berggren and Miller (1988) used the HO of <i>T. cerroazulensis</i> (rather than that of <i>Hantkenina</i>) to denote the P17/P18 zonal boundary because of its greater potential for preservation.
3. <i>Cribrohantkenina inflata</i>	X	C13r	34.0	1-4		=P16/P17 boundary of Blow (1979) and Berggren and Miller (1988). Located between LAD of <i>Glo. index</i> and <i>T. cunialensis</i> and <i>Hantkenina</i> in mid-part of C13r at Massignano (ref. 4) and just below youngest of 3 normal "events" in C13r in Contessa Highway section (ref. 2).
4. <i>Globigerapsis index</i>	X	C13r	34.3	1-5		Essentially coincident with the LAD of <i>Discoaster saipanensis</i> and <i>Discoaster barbadoensis</i> and with lower of 3 normal "events" in C13r in Contessa Highway section (refs. 2, 3). Occurs in younger part of C13r on Kerguelan Plateau (Site 748) (ref. 5) and then appears to be globally reliable datum. Recorded at a level in Hole 689B (Weddell Sea) identified as C16n (ref. 6), but an alternative interpretation of the paleomagnetic stratigraphy (ref. 5) suggests this may be C15n, in which case the (apparent) latitudinal diachrony of the HO of <i>Glo. index</i> would be significantly reduced, if not eliminated, inasmuch as dissolution is strong across the Eocene/Oligocene boundary interval at high latitudes.
5. <i>Turborotalia cunialensis</i>	X	C15r	35.2	2-4		Just above (i.e., younger than) LAD of <i>P. semiinvoluta</i> (refs. 2, 3).
6. <i>Turborotalia pomeroli</i>	X	C15r	35.3	1-3		HO of <i>P. semiinvoluta</i> in Massignano section (ref. 4).
7. <i>Porticulasphaera semiinvoluta</i>	X	C15r _(o)	35.3	1-3		Located in C16n.2n in Massignano section (ref. 4).
8. <i>Cribrohantkenina inflata</i>	X	(C16n or oldest part of C15r)	(35.5)	3,4		=P15/P16 boundary of Blow (1979) and Berggren and Miller (1988). Occurs between FAD of <i>Isthmolithus recurvus</i> and LAD of <i>P. semiinvoluta</i> and <i>T. pomeroli</i> in Spain (Molina, 1986; Monechi, 1986; Molina and others, 1986). FAD of <i>I. recurvus</i> is in C16n.2n (refs. 1-4) and LADs of <i>T. pomeroli</i> and <i>P. semiinvoluta</i> occur in C15r in Contessa Highway (refs. 1-3) or C16n.2n, in Massignano section (ref. 4) which suggests that FAD of <i>C. inflata</i> corresponds approximately with C16n.2n. FAD not considered unequivocally determined (ref. 3). Brief overlap of <i>C. inflata</i> and <i>P. semiinvoluta</i> shown in the upper part of <i>G. semiinvoluta</i> Zone = lower Zone P16 of Blow (1979) in Toumarkine and Luterbacher (1985).
9. <i>Acarinina collectae</i>	X	C17n	37.7	1		Recorded in interval of uninterpretable paleomagnetic data just above level identified as C17n in Hole 748B (ref. 5) and at level interpreted as C18n in Hole 690B (Weddell Sea) (ref. 6).
10. <i>Subbotina linaperta</i>	X	C17n, In	37.7	5,6		Recorded in mid-C17n in Hole 689B (ref. 6) and in C17n in Hole 748B (ref. 6).
11. <i>Morozovella spinulosa</i>	X	C17n _(o)	38.1	1		
12. <i>Porticulasphaera semiinvoluta</i>	X	C18n _(y)	38.4	1,2		=P14/P15 zonal boundary of Blow (1979) and Berggren and Miller (1988). Note brief overlap of <i>Truncorotaloides</i> and <i>P. semiinvoluta</i> (Blow, 1979) but brief but distinct separation of <i>Acarinina</i> and <i>P. semiinvoluta</i> in ref. 2, Fig. 1.
13. <i>Planorotalites</i>	X	C18n _(y)	38.5	2		
14. <i>Acarinina primitiva</i>	X	C18n	39.0	1,6		Recorded in mid-part of C18n in Hole 689 (ref. 6) and in interval of uninterpretable paleomagnetic data just above probable C18n in Hole 748B (ref. 5).
15. <i>Acarinina</i> spp.	X	C17n-C18n	37.5-38.5	1,2		Mid-C17n (ref. 1) or top C18n (refs. 2, 3) in the Apennines.
16. <i>Subbotina frontosa</i>	X	C18n (mid)	39.3	1		
17. <i>Globigerapsis beckmanni</i>	X	C18n _(o)	40.1	1		P13/P14 boundary in Berggren and Miller (1988).
18. <i>Globigerapsis beckmanni</i>	X	C18r	40.5	1		P12/P13 boundary in Berggren and Miller (1988).
19. <i>Acarinina bullbrookii</i>	X	C18r	40.5	1		
20. <i>Turborotalia pomeroli</i>	X	C19r	42.4	1		
21. <i>Globigerapsis index</i>	X	C20n	42.9	1		Recorded near C20n/C20r boundary in Hole 689B (ref. 6).
22. <i>Morozovella lehneri</i>	X	C20n	43.5	1		
23. <i>Morozovella aragonensis</i>	X	C20n	43.6	1		=P11/P12 boundary in Berggren and Miller (1988).
24. <i>Turborotalia possagnoensis</i>	X	C20r	46.0			
25. <i>Hantkenina nuttalli</i>	X	C22n _(y)	49.0	1		=P9/P10 zonal boundary in Berggren and Miller (1988).
26. <i>Planorotalites palmerae</i>	X	C22r	50.4	1		=P8/P9 zonal boundary in Berggren and Miller (1988).
27. <i>Acarinina pentacamerata</i>	X	C23n, 1n _(y)	50.8	6		Recorded at top of C23n in Hole 689 (ref. 6).
28. <i>Morozovella aragonensis</i>	X	C23n, 2r	52.3	7-10		=P6c/P7 zonal boundary of Berggren and Miller (1988). Recorded in C23r in Holes 550 (refs. 7, 8), 577 (refs. 9, 10) and 527 (ref. 9).
29. <i>Morozovella marginodentata</i>	X	C24n, 1r	52.5	7,8		Hole 550 (refs. 7, 8).
30. <i>Morozovella lensiformis</i>	X	C24n, 1r	52.7	7-9		Holes 550 (refs. 7, 8) and 577 (ref. 9).
31. <i>Subbotina velascoensis</i>	X	C24r	53.5	7,8		Hole 550 (refs. 7, 8).
32. <i>Morozovella aqua</i>	X	C24r	53.6	7-9		Hole 550 (refs. 7, 8); C24n, 1n in Hole 577 (ref. 9).
33. <i>Morozovella formosa</i>	X	C24r	54.0	9		=P6b/c subzonal boundary of Berggren and Miller (1988). Hole 577 (ref. 9).
34. <i>Morozovella lensiformis</i>	X	C24r	54.0	7-9		Holes 550 (refs. 7, 8) and 577 (ref. 9).

TABLE 9.—Continued.
EOCENE

Datum	FAD	LAD	Paleomagnetic Chron	Age in Ma	Reference	Remarks
35. <i>Morozovella velascoensis</i>	X	X	C24r	54.7	1	Recorded in younger part of C24r in Hole 577 (ref. 9) and in mid-part C24r in Hole 577 (at 81.98 m) (ref. 11). However, paleomagnetic data (Bleil, 1985, p. 449, Fig. 7b) suggest that a hiatus occurs between ~82 and 83 m in Hole 577, which would have the effect of depressing (rendering older) the HO of <i>M. velascoensis</i> . The HO of <i>M. velascoensis</i> in Hole 577 is in CP8 (=NP9) (Monechi, 1985, p. 310, Table 5) which supports interpretation of hiatus in Hole 577, because the LAD of <i>M. velascoensis</i> is in Zone NP10. Furthermore Monechi (1985, p. 307) indicates absence of Subzone CP9a at ~81-m in Hole 577 and/or an interval of extremely condensed sedimentation across the Paleocene/Eocene boundary interval.
36. <i>Morozovella acuta</i>	X	X	C24r (mid)	54.7	8	Hole 550; located midway between -17 and +19 (54.0 Ma) Ashes.
37. <i>Morozovella formosa gracilis</i>	X	X	C24r (mid)	54.7	7-9	Hole 550 (refs. 7, 8).
38. <i>Muricella broedermani</i>	X	X	C24r (mid)	54.7	7-9	Hole 550 (refs. 7, 8).
39. <i>Morozovella marginodentata</i>	X	X	C24r (lower)	54.8	7-9	Hole 550 (refs. 7, 8); Hole 577, top C25n (ref. 9).
40. <i>Globanomalina australiformis</i>	X	X	C24r	55.5	6	= AP4/AP5 zonal boundary of Stott and Kennett (1990); Holes 689B, 690B (ref. 6), used to denote P/E boundary in high austral latitudes. Recorded also at Sites 738 (ref. 12) 747 and 748 (ref. 5) but with no paleomagnetic control.

¹Berggren and others, 1985b²Nocchi and others, 1986³Premoli-Silva and others, 1988a⁴Coccioni and others, 1988⁵Berggren, 1992⁶Stott and Kennett, 1990⁷Snyder and Waters, 1985⁸Berggren (this work)⁹Corfield, 1987¹⁰Liu and Olsson (pers. commun., 1993)¹¹Pak and Miller, 1993¹²Huber, 1991

P18 rather than the LAD of *Hantkenina* spp. for the reasons cited in Berggren and Miller (1988, p. 375), namely the greater robustness and frequency of the former in latest Eocene assemblages, while at the same time recognizing that the LAD of both these groups may ultimately be shown to be simultaneous. As defined and applied here the P17/P18 zonal boundary would be about 0.1 my older than the Eocene/Oligocene boundary as denoted (not defined) by the LAD of *Hantkenina* spp.

Oligocene zonation.—The chronology of Oligocene (sub)tropical planktonic foraminiferal datum events/zones is shown in Figure 10.

P18. *Turborotalia cerroazulensis-Pseudohastigerina* spp. Interval Zone (herein defined; emendation of Zone P18 of Berggren and Miller, 1988)

Definition: Biostratigraphic interval between the LAD of *Turborotalia cerroazulensis* and the LAD of *Pseudohastigerina* spp.

Magnetochronologic calibration: Chron C13r (late)-Chron C12r

Estimated age: 33.8–32.0 Ma; early Oligocene (early Rupelian)

Remarks: Berggren and Miller (1988, p. 375) substituted the partial range of *Chiloguembelina cubensis* for *Cassigerinella chipolensis* in modifying Bolli and Saunders' (1985) lowermost Oligocene zone because of the irregular occurrence of *chipolensis* in lower Oligocene sections. Zone P18 is exactly correlative with the *C. chipolensis/Ph. micra* Concurrent Range Zone of Bolli and Saunders (1985) and Zones P18 and P19 of Blow (1969; see further discussion in Berggren and Miller, 1988, p. 375). The zonal denotation has been changed from a partial range to an interval zone here to provide easier recognition of this zone on a regional basis (i.e., the erratic occurrence of *Ch. cubensis* in shallower (marginal) deposits renders it less useful in these areas).

P19. “*Turborotalia*“ ampliapertura Interval Zone (P19 of Berggren and Miller, 1988)

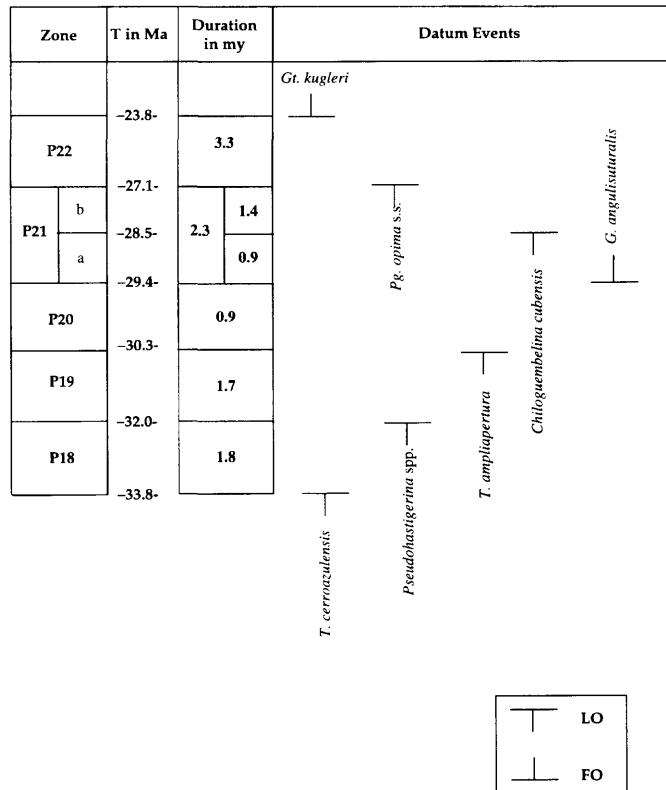


FIG. 10.—Chronology of Oligocene (sub)tropical planktonic foraminiferal zones.

Definition: Biostratigraphic interval between the LAD of *Pseudohastigerina* spp. and the LAD of “*Turborotalia*“ ampliapertura

Magnetochronologic calibration: Chron C12r-Chron C11r

Estimated age: 32.0–30.3 Ma; late early Oligocene (late Rupelian)

Remarks: The historical vicissitudes associated with this zone are discussed in detail by Berggren and Miller (1988, p. 375).

P20. *Globigerina sellii* Partial Range Zone (P20 of Berggren and Miller, 1988)

Definition: Biostratigraphic interval characterized by the partial range of the nominate taxon between the LAD of “*Turborotalia ampliapertura*” and the FAD of *G. angulisuturalis*.

Magnetostratigraphic calibration: Chron C11r-Chron C11n(y)

Estimated age: 30.3–29.4 Ma; late early Oligocene (late Rupelian)

Remarks: Spinose paragloborotaliids (*opima* s.s.), small (*ciperoensis*, *praebulloides*, *anguliofficinalis*) and large (*tapuriensis*, *sellii*) globigerinids and subbotinids (*angiporooides*), which has its LAD within the mid-part of this zone), and microperforate tenuitellids (*gemma*, *munda*) characterize Zone P20. Further discussion may be found in Berggren and Miller (1988, p. 376).

P21. *Globigerina angulisuturalis/Paragloborotalia opima opima* Concurrent Range Zone (P21 of Blow, 1969, 1979; P21 of Berggren, 1969; Berggren and Miller, 1988)

Definition: Biostratigraphic interval characterized by the concurrent range of the nominate taxa between the FAD of *Globigerina angulisuturalis* and the LAD of *Paragloborotalia opima opima*.

Magnetostratigraphic calibration: Chron C11n(y)-Chron C9n(y)

Estimated age: 29.4–27.1 Ma; latest early-early late Oligocene (latest Rupelian-early Chattian)

Remarks: This zone is subdivided into two subzones based on the virtual extinction of chiloguembelinids in the midpart of the zone. Further discussion is given in Blow (1969) and Berggren and Miller (1988, p. 376).

P21a. *Globigerina angulisuturalis/Chiloguembelina cubensis* Concurrent Range Subzone (P21a of Berggren and Miller, 1988)

Definition: Biostratigraphic interval characterized by the concurrent range of the nominate taxa between the FAD of *Globigerina angulisuturalis* and the LAD of *Chiloguembelina cubensis*.

Magnetostratigraphic calibration: Chron C11n(y)-Subchron C10n.1n

Estimated age: 29.4–28.5 Ma; latest early Oligocene (latest Rupelian)

Remarks: See Berggren and Miller (1988, p. 376) for additional information.

P21b. *Globigerina angulisuturalis-Paragloborotalia opima opima* Interval Subzone (P21b of Berggren and Miller, 1988; see also Jenkins and Orr, 1972)

Definition: Biostratigraphic interval between the (virtual) LAD of *Chiloguembelina cubensis* and the LAD of *Paragloborotalia opima opima*.

Magnetostratigraphic calibration: Chron C10n.1n-Chron C9n(y)

Estimated age: 28.5–27.1 Ma; early late Oligocene (early Chattian)

Remarks: The use of the LAD of *Ch. cubensis* to subdivide the P21 Zone of Blow (1969) was initially suggested by Jenkins and Orr (1972) in the eastern Equatorial Pacific. It has since found wide application in both (sub)tropical (BKF85; Berggren and Miller, 1988) as well as in high southern (Berggren, 1992) latitude biostratigraphies.

P22. *Globigerina ciperoensis* Partial Range Zone (Cushman and Stainforth, 1945; emended by Bolli, 1957b; P22 of Berggren and Miller, 1988)

Definition: Biostratigraphic interval characterized by the partial range of the nominate taxon between the LAD of *Paragloborotalia opima opima* and the FAD of *Globorotalia kugleri* sensu stricto.

Magnetostratigraphic calibration: Chron C9n(y)-Chron C6Cn.2n(o)

Estimated age: 27.1–23.8 Ma; late Oligocene (Chattian)

Remarks: The historical vicissitudes of this zone are discussed in greater detail in Berggren and Miller (1988, p. 376).

Neogene zonation.—

The use of planktonic foraminifera to biostratigraphically subdivide (sub)tropical marine Neogene stratigraphies began essentially in the 1940s with petroleum exploration in the Caribbean region (Cushman and Stainforth, 1945). The zonal schemes of Bolli (1957b, 1966), Banner and Blow (1965), Blow (1969, 1979), developed primarily in connection with petroleum exploration in the Caribbean region in the post-World War II years, have been reviewed by Stainforth and others (1975). Modifications to Blow's (1969, 1979) N-zone scheme have been made by Srinivasan and Kennett (1981a, b) and alternate/modified zonal stratigraphies developed by Thunell (1981) and Berggren and others (1985a). More recently Saunders and Bolli (1983) and Bolli and Saunders (1985) have provided an overview of the history of (sub)tropical planktonic foraminiferal biostratigraphic zonal schemes. Various zonal schemes have also been adopted for use in the Mediterranean region, the most commonly used one for the Pliocene Series being that of Cita (1973, 1975).

Mid-(temperate/transitional) and high-latitude Neogene biostratigraphies and evolutionary trends have been developed/reviewed by Jenkins (1967, 1971, 1975, 1992, 1993a, b), Srinivasan and Kennett (1981a, b; 1983), Kennett and Srinivasan (1983, 1984), Berggren (1973, 1977a, b, 1992) and Berggren and others (1983a), predominantly for Southern Hemisphere stratigraphies, whereas Northern Hemisphere zonal stratigraphies have been developed/discussed by, among others, Berggren (1972), Poore and Berggren (1975) and Weaver and Clement (1986; North Atlantic) and Keller (1979a-c, 1980a, b, 1981; Pacific).

As part of our attempt to provide a revised calibration of Neogene planktonic foraminiferal biostratigraphy to the new GPTS of CK92/95, we have reviewed the current status of existing planktonic zonal schemes and attempted to formulate a unified one that reflects our current understanding of planktonic foraminiferal biogeography. The problem we have faced is that while various aspects of both the Bolli (1957b, 1966) and Blow (1969, 1979) (sub)tropical scheme are fully acceptable for a zonal stratigraphy, other parts of the zonal schemes are less applicable (see Berggren, 1973, 1977a, 1993). Berggren and

others (1983a) and Brönnimann and Resig (1971) reviewed some of the shortcomings of the zonal definitions and applications of Zones N17-N21 of Blow (1969) shortly after their formulation. Recall that Blow's ideas on Neogene planktonic foraminiferal zonation were already formed in the late 1960s; he died in 1972 but revisions to his Neogene zonal scheme were only published posthumously in 1979 and the need for a set of multiple zones reflecting regional biogeographies has been stressed by Jenkins and Orr (1972), Kennett (1973), Srinivasan and Kennett (1983), among others. It is with this in mind that we have attempted a modification/unification of these schemes in the past and herein. In applying a numerical notation scheme to what are, in some instances, the same zonal concepts as previous authors, we wish to emphasize that we do not seek, nor accept, credit for creating a "new" zonal stratigraphy (other than for those (sub)zones defined as "new" here or in previous work(s)). Unification of existing schemes with a view to providing improved biochronologic subdivisions reflecting regional biogeographies is the main goal of this exercise. For instance, in a recent study of some of Blow's (1969) Jamaican (para)type localities for Zones N16-N21, Berggren (1993) has demonstrated the inadequacies of Zones N18-N21 (at least) and suggested the use of alternate schemes. In the sections below, we shall review the state of Neogene planktonic foraminiferal biostratigraphy and suggest zonal biostratigraphies (converted to biochronologies) appropriate to regional biogeographies. In the case of the (sub)tropical regions, some workers may prefer simply to refer to, or utilize, the Bolli or Blow zonal stratigraphy in their work. The M-zonal scheme developed here is simply meant to provide continuity with the Pliocene Pl-zonal scheme developed earlier (and modified here) for (sub)tropical regions by combining the best (in our judgment) components of previous zonal schemes into a single, unified system.

Miocene Zonation of (Sub)Tropical Regions.—The chronology of early and middle-late Miocene (sub)tropical planktonic foraminiferal datum events/zones is shown in Figures 11 and 12, respectively.

The notation "M" used by Berggren (in Berggren and others, 1983a) to denote a series of Miocene subtropical-transitional zones for (predominantly) South Atlantic subtropical-transitional stratigraphies is preempted here to denote a zonal scheme applicable to tropical-subtropical regions. The notation "Mt" is used to denote a zonal scheme applicable to (predominantly) transitional Miocene faunas (see below).

M1. *Globorotalia kugleri* Total Range Zone (M1; Berggren and others, 1983a)

Definition: Total range of the nominate taxon

Magnetochronologic calibration: Subchron C6Cn. 2n(o)-Chron C6Ar

Estimated age: 23.8–21.5 Ma; early Miocene (Aquitianian)

Remarks: See comments by Blow (1969), Srinivasan and Kennett (1981b, 1983) and Berggren and others (1983a) regarding the history of this, and closely related zones.

M1a. *Globigerinoides primordius* Interval Subzone (M1a; Berggren and others, 1983a)

Definition: The biostratigraphic interval characterized by the nominate taxon between the FAD of *Globorotalia kugleri* and the FAD of *Globoquadrina dehiscens*

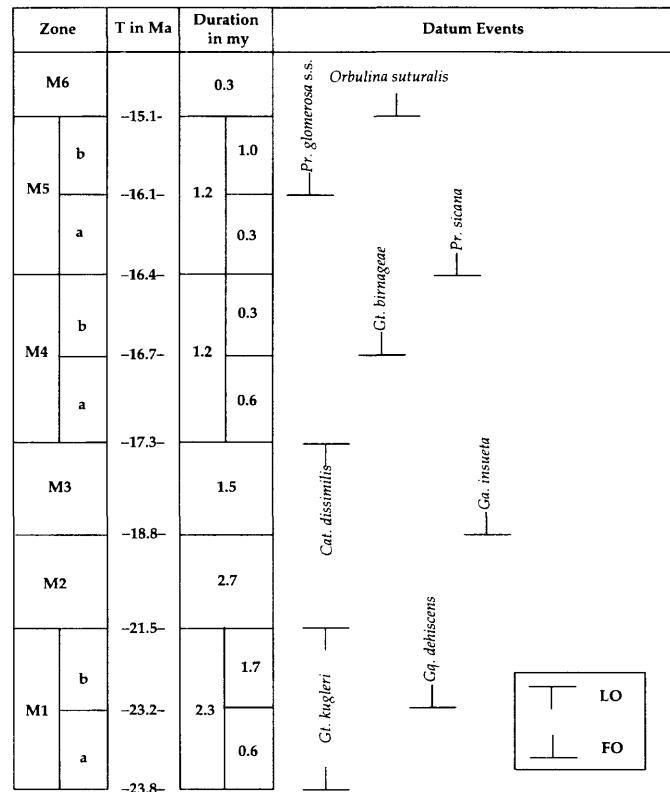


FIG. 11.—Chronology of early Miocene (sub)tropical planktonic foraminiferal zones.

Magnetochronologic calibration: Subchron C6Cn. 2n(o)-Chron C6Br

Estimated age: 23.8–23.2 Ma; early Miocene (Aquitianian)

Remarks: Srinivasan and Kennett (1981b) emended Blow's (1969) *Globoquadrina quadrilobatus primordius/Globorotalia (Turborotalia) kugleri* Concurrent Range Zone (N4) and subdivided it into a lower *Gl. primordius/Gt. kugleri* "Concurrent Range" Subzone using the FAD of *Gd. primordius* and the FAD of *Gq. dehiscens* as lower and upper boundary criteria, respectively. This definition, in effect, renders this an interval zone; it would represent a concurrent range zone if the LAD of *Gt. kugleri* were used to denote its upper boundary. Berggren in Berggren and others (1983a) returned to the original concept of a *Gt. kugleri* Total Range and subdivided it into two parts based on the basis of the FAD of *Gq. dehiscens* within the range of *Gt. kugleri*. A characteristic element of upper Oligocene and lowermost Miocene faunas is the development of early forms of *Globigerinoides (Gd. primordius)* and this has been found to be useful to denote this subzone.

M1b. *Globorotalia kugleri/Globoquadrina dehiscens* Concurrent Range Subzone (M1b; Berggren and others, 1983a=Zone N4b of Srinivasan and Kennett, 1981b)

Definition: The biostratigraphic interval characterized by the concurrent range of the nominate taxa between the FAD of *Globoquadrina dehiscens* and the LAD of *Globorotalia kugleri*

Magnetochronologic calibration: Chron C6Br-Chron C6Ar

Estimated age: 23.2–21.5 Ma

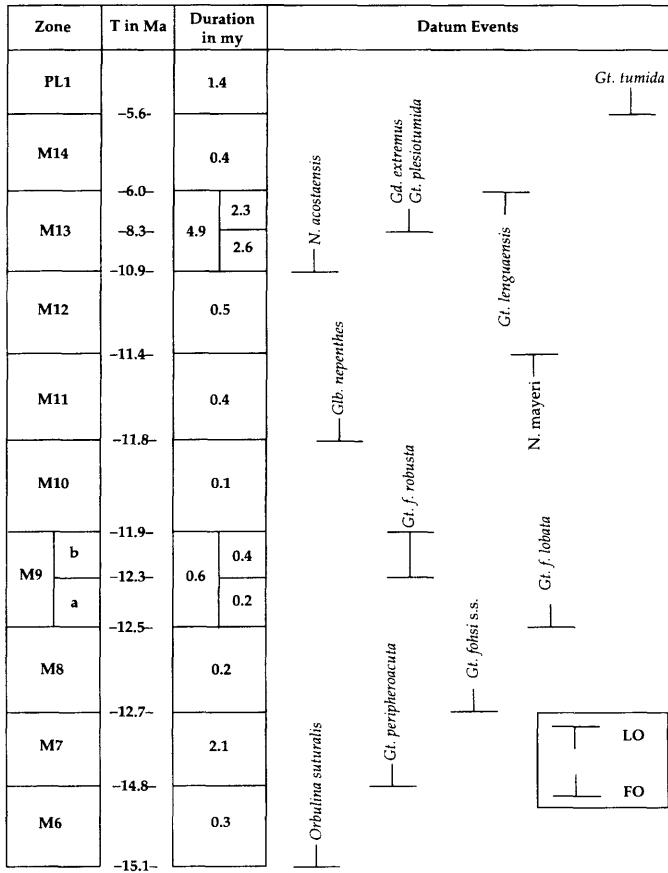


FIG. 12.—Chronology of middle-late Miocene (sub)tropical planktonic foraminiferal zones.

Remarks: This subzone corresponds to the upper part of the *Globoquadrina quadrilobatus primordius/Globorotalia (Turborotalia) kugleri* Zone of Blow (1969, 1979).

M2. *Catapsydrax dissimilis* Partial Range Zone (M2; Cushman and Renz, 1947, emend. Bolli, 1957b; = Zone N5 of Blow, 1969, 1979)

Definition: Biostratigraphic interval characterized by the partial range of the nominate taxon between the LAD of *Globorotalia kugleri* and the FAD of *Globigerinatella insueta*.

Magnetostratigraphic calibration: Chron C6Ar-Chron C5En (inferred)

Estimated age: 21.5–18.8 Ma; early Miocene (Burdigalian)

Remarks: This zone (as emended by Bolli, 1957b) and Zone N5 (Blow, 1969, 1979) have the same boundary criteria. The common occurrence of *Cat. dissimilis* in this interval prompts us to utilize this zone in the sense of Bolli (1957b). The magnetostratigraphic calibration of the M2/M3 zonal boundary is inferred inasmuch as there is no direct calibration for the FAD of *Ga. insueta* at present.

M3. *Globigerinatella insueta/Catapsydrax dissimilis* Concurrent Range Zone (M3; Blow, 1969, 1979; = N6)

Definition: The concurrent range of the nominate taxa between the FAD of *Globorotalia insueta* and the LAD of *Catapsydrax dissimilis* and/or *Catapsydrax unicavus*.

Magnetostratigraphic calibration: Chron C5En (inferred)-Chron C5Dn(y)

Estimated age: 18.8–17.3 Ma; early Miocene (Burdigalian)

Remarks: We use this zone as defined by Blow (1969, 1979). The LAD of *Catapsydrax* spp. represents a distinct bioevent which occurs in transitional and high-latitude areas as well and serves as a point of regional correlation in the late early Miocene.

M4. *Catapsydrax dissimilis-Praeorbulina sicana* Interval Zone (M4; here defined; = N7 of Blow, 1969, 1979)

Definition: Biostratigraphic interval between the LAD of *Catapsydrax dissimilis* and/or *Catapsydrax unicavus* and the FAD of *Praeorbulina sicana*.

Magnetostratigraphic calibration: Chron C5Dn(y)-Chron C5Cn.2n

Estimated age: 17.3–16.4 Ma; early Miocene (late Burdigalian)

Remarks: As defined here this zone corresponds to Zone N7 of Blow (1969, 1979) in extent, if not intent, and to the lower part of the *Globigerinatella insueta* Interval Range Zone of Cushman and Stainforth (1945; as emended by Bolli, 1957b).

M4a. *Catapsydrax dissimilis-Globorotalia birnageae* Interval Subzone (M4a; here defined)

Definition: Biostratigraphic interval between the LAD of *Catapsydrax dissimilis* and/or *Catapsydrax unicavus* and the FAD of *Globorotalia birnageae*.

Magnetostratigraphic calibration: Chron C5Dn(y)-Chron C5Cn.3n(o)

Estimated age: 17.3–16.7 Ma; early Miocene (late Burdigalian)

Remarks: Zone M4 is a relatively short zone (<1 my) within which biostratigraphic differentiation has been found possible under certain circumstances. The FAD of *Gt. birnageae* occurs within the biostratigraphic interval denoted by the bounding criteria of Zone M4 and has been found useful in various tropical-subtropical stratigraphies (e.g., Gulf of Mexico, Caribbean, Mediterranean).

M4b. *Globigerinoides bisphericus* Partial Range Zone (M4b; here defined)

Definition: Biostratigraphic interval characterized by the partial range of the nominate taxon between the FAD of *Globorotalia birnageae* and the FAD of *Praeorbulina sicana*.

Magnetostratigraphic calibration: Subchron C5Cn.3n(o)-Subchron C5Cn.2n

Estimated age: 16.7–16.4 Ma; late early Miocene (late Burdigalian)

Remarks: We follow the differentiation made by Jenkins and others (1981) between *Pr. sicana* and *Gd. bisphericus* (see discussion below under Zone M5). Precise determination of the FAD of *Gd. bisphericus* is difficult because of its intergradation with *Gl. trilobus* sensu stricto, and we have recently found (Zhang and others, 1993) morphotypes referable to this taxon in Gulf of Mexico Eureka cores at levels referable to Zone M3 (= N6 of Blow, 1979). However, the taxon is well developed in its typical morphology in the younger part of the early Miocene (latest Burdigalian) and for that reason we use it as a partial range subzone to characterize/subdivide Zone M4.

M5. *Praeorbulina sicana*-*Orbulina suturalis* Interval Zone (M5; here defined; = N8 of Blow, 1969, 1979)

Definition: Biostratigraphic interval between the FAD of *Praeorbulina sicana* and the FAD of *Orbulina suturalis*

Magnetostratigraphic calibration: Subchron C5Cn.2n-Subchron C5Bn.2n

Estimated age: 16.4–15.1 Ma; middle Miocene (Langhian)

Remarks: This zone corresponds in extent to the upper part of the *Globigerinatella insueta* Zone of Cushman and Stainforth (1945; as emended by Bolli, 1957b) and to Zone N8 of Blow (1969, 1979). The evolutionary transition from *Praeorbulina* to *Orbulina* occurs within this zone and while the relatively rapid morphologic transitions between “taxa” of the *glomerosa* group in Zone M5 are often difficult to discern owing to preservational bias; the sequential development of the component morphotypes allows a high-resolution discrimination under ideal preservational circumstances. Under these, a two-fold subdivision has been found practical (see below). This zone corresponds fully to Zone Mt5 in the temperate-transitional regions where the *praeorbulinid*-*orbulinid* bioseries is generally found owing to the significant late early and early middle Miocene warming which brought these forms to higher latitudes.

An examination of the type material led Jenkins and others (1981) to differentiate the taxa *bisperricus* and *sicana* (formerly considered synonymous by many workers) on the basis of the greater degree of enrollement of the test by the final chambers, reduction in size of, and concomitant increase in number of, supplementary apertures, absence of discernible umbilicus and greater test sphericity in *sicana*. They noted that the base of Blow's (1969, 1979) Zone N8 was defined using the concept of *sicana* (non *bisperricus*), redefined the N7/N8 zonal boundary to coincide with the subsequent FAD of *Pr. glomerosa curva* and observed that there is no significant temporal reduction in Zone N8 as previously defined. Indeed, our magnetostratigraphic tabulations suggest that the FADs of the two taxa are separated by only 0.1 my. We have chosen to use the FAD of *Pr. glomerosa glomerosa*, rather than that of *Pr. glomerosa curva*, to subdivide Zone M5, because of the somewhat larger temporal and morphologic separation between the FAD of these two taxa which we believe allows more reliable and consistent recognition and differentiation of these two biostratigraphic intervals.

The FAD of *Pr. sicana* is used to denote the base of the Langhian Stage and the lower/middle Miocene boundary (Cita and Blow, 1969) although precise correlation has not been demonstrated between the two. If the FAD of this taxon occurs somewhat lower (in the Cortemilia Formation) than the base of the stratotype Langhian Stage, the Burdigalian/Langhian (lower/middle Miocene) boundary may be more closely associated with the FAD of *Pr. glomerosa glomerosa* (Chron C5Cn.1n; 16.1 Ma).

M5a. *Praeorbulina sicana*-*Praeorbulina glomerosa* sensu stricto Interval Subzone (M5a; here defined)

Definition: Biostratigraphic interval between the LAD of *Praeorbulina sicana* and the FAD of *Praeorbulina glomerosa* sensu stricto

Magnetostratigraphic calibration: Subchron C5Cn.2n-Subchron C5Cn.1n

Estimated age: 16.4–16.1 Ma; earliest middle Miocene (earliest Langhian)

Remarks: This subzone corresponds to the upper part of the *Globigerinatella insueta* Zone of Cushman and Stainforth (1945; as emended in Bolli, 1957b) and to the lower part of Zone N8 of Blow (1969, 1979).

M5b. *Praeorbulina glomerosa* sensu stricto-*Orbulina suturalis* Interval Subzone (M5b; here defined)

Definition: Biostratigraphic interval between the FAD of *Praeorbulina glomerosa* sensu stricto and the FAD of *Orbulina suturalis*

Magnetostratigraphic calibration: Subchron C5Cn.1n-Subchron C5Bn.2n

Estimated age: 16.1–15.1 Ma; early Miocene (Langhian)

Remarks: This subzone corresponds closely, but not precisely, to the *Praeorbulina glomerosa* Zone of Jenkins (1967) and Srinivasan and Kennett (1981b, 1983) in which the FAD of *Pr. glomerosa curva* was used to denote the base of the zone. It also corresponds to the upper part of Zone N8 of Blow (1969, 1979).

M6. *Globorotalia peripheroronda* Partial Range Zone (M6; = Zone N9 of Blow (1969, 1979))

Definition: Biostratigraphic interval characterized by the partial range of the nominate taxon between the FAD of *Orbulina suturalis* and the FAD of *Globorotalia peripheroacuta*

Magnetostratigraphic calibration: Subchron C5Bn.2n-Chron C5Bn(y)

Estimated age: 15.1–14.8 Ma; middle Miocene (Langhian)

Remarks: This zone corresponds fully to Blow's (1969, 1979) Zone N9, and we would agree with Blow's (1969, p. 231) assessment that the FAD of *O. suturalis* provides a more widespread and easily recognizable datum event than the LAD of *Ga. insueta* used by Bolli (1957b, 1966, and retained by Bolli and Saunders, 1985) for denoting the base of the *Gt. peripheroronda* “Interval Range Zone” (actually a partial range zone as defined by Bolli, 1957b).

M7. *Globorotalia peripheroacuta* Lineage Zone (M7; here defined; = Zone N10 of Blow, 1969; 1979)

Definition: Biostratigraphic interval between the initial evolutionary appearance of the nominate taxon and the initial evolutionary appearance of *Globorotalia foehsi* sensu stricto

Magnetostratigraphic calibration: Chron C5Bn(y)-Subchron C5Ar.1n

Estimated age: 14.8–12.7 Ma; middle Miocene (Serravallian)

Remarks: Bolli and Saunders (1985, p. 215) have pointed out the advanced biocharacters of the holotype of *Gt. praefohsi* Blow and Banner (1966) and suggested that it is a form intermediate between *Gt. foehsi* sensu stricto and *Gt. foehsi lobata*, a view supported by the fact that the holotype of *praefohsi* is from the *Globorotalia foehsi lobata* Zone in Venezuela. The paratype of *praefohsi* appears to be intermediate between *peripheroacuta* and *foehsi* sensu stricto, but inasmuch as the species concept is based upon the holotype, this observation is irrelevant to the definition of *Gt. praefohsi*. Thus, we prefer to use *Gt. foehsi* sensu stricto as the nominate form of Zone M8. In all likelihood, Blow (1969, 1979), in using both the holotype and paratype of *praefohsi* as concept of the species, would have placed the N10/N11 zonal boundary at the same level as we have placed the Zone M7/M8 boundary, inasmuch as the FAD of *Gt. foehsi* sensu

stricto and *Gt. praefohsii* (sensu paratype) are at about the same level according to our investigations.

M8. *Globorotalia foehsi* sensu stricto Lineage Zone (M8; = *Globorotalia foehsi foehsi* Lineage Zone of Cushman and Stainforth, 1945; emended by Bolli, 1957b)

Definition: Biostratigraphic interval between the initial evolutionary appearance of the nominate taxon and the initial evolutionary appearance of *Globorotalia foehsi lobata*

Magnetostratigraphic calibration: Subchron C5Ar.1n-Subchron C5Ar.1r

Estimated age: 12.7–12.5 Ma; middle Miocene (Serravallian)

Remarks: The revised isotopically based interpretation of the magnetostratigraphy of DSDP Hole 563 (Wright and Miller, 1992) indicates that the FAD of *Gt. foehsi lobata* occurs in Chron C5Ar.1r rather than in Chron C5AAr (Miller and others, 1985).

M9. *Globorotalia foehsi lobata-Globorotalia foehsi robusta* Interval Zone (M9; = combined *Gt. foehsi lobata* Interval Zone of Bolli, 1957b and *Gt. foehsi robusta* Taxon Range Zone of Bolli, 1957b)

Definition: Biostratigraphic interval between the initial (evolutionary) appearance of *Globorotalia foehsi lobata* to the LAD of its descendant *Globorotalia foehsi robusta*

Magnetostratigraphic calibration: Subchron C5Ar.1r-Subchron C5An.1n

Estimated age: 12.5–11.9 Ma; middle Miocene (Serravallian)

Remarks: This zone is combined in the sense of Stainforth and others (1975, p. 82) because of the difficulty in some instances/areas in discerning the component parts of the evolutionary sequence from *lobata* to *robusta*. Zone M9 is subdivided into two subzones based on the sequential FADs of these two “subspecies” for use in those circumstances where this sequence is recognizable. The magnetostratigraphic calibration of the nominate taxa of the boundaries of Subzones M9a and M9b is based on a reinterpretation of the original magnetostratigraphy in DSDP Hole 563 (Wright and Miller, 1992).

M9a. *Globorotalia foehsi lobata* Lineage Zone (M9a; = *Globorotalia foehsi lobata* Lineage Zone of Bolli, 1957b)

Definition: Biostratigraphic interval between initial evolutionary appearance of nominate taxon and that of its descendant *Globorotalia foehsi robusta*

Magnetostratigraphic calibration: Subchron C5Ar.1r-Subchron C5An.2n

Estimated age: 12.5–12.3 Ma

Remarks: See remarks on Zone M9 above.

M9b. *Globorotalia foehsi robusta* Total Range Zone (M9b; = *Globorotalia foehsi robusta* Total Range Zone of Bolli, 1957b)

Definition: Biostratigraphic interval characterized by the total range of the nominate taxon.

Magnetostratigraphic calibration: Subchron C5An.2n-Subchron C5An.1n

Estimated age: 12.3–11.9 Ma; middle Miocene (Serravallian)

Remarks: See remarks under Zone M9 above.

M10. *Globorotalia robusta-Globoturboralita nepenthes* Interval Zone (M10; here defined)

Definition: Biostratigraphic interval between the LAD of *Globorotalia foehsi robusta/lobata* and the FAD of *Globoturboralita nepenthes*

Magnetostratigraphic calibration: Subchron C5An.1n-Subchron C5r.3r

Estimated age: 11.9–11.80 Ma; middle Miocene (Serravallian)

Remarks: In Jamaica we (Berggren, 1993) have observed the same sequence of bioevents as denoted by Bolli (1966; see also Bolli and Saunders, 1985, p.167) as well as in the expanded mid-Miocene section in the Bodjonegoro-1 well of Indonesia, namely LAD of *Gt. foehsi robusta*, LAD of *Gl. subquadratus*, LAD of *N. mayeri* (with the FAD of *Glb. nepenthes* occurring approximately midway within the 25-m interval separating the latter two datums in Jamaica). Using the magnetostratigraphic calibration of the LAD of *Gt. foehsi robusta* of Chron C5An.1n (DSDP Hole 563; Miller and others, 1985), the FAD of *Glb. nepenthes* of Chron C5r.3r (DSDP Hole 563; Miller and others, 1985) and the LAD of *N. mayeri* of Chron C5r.2r (Buff Bay section; Miller and others, 1994), we have calculated that the LAD of *Gd. subquadratus* is ~0.05 my younger than the LAD of *Gt. foehsi robusta*. In view of the fact that we have estimated the duration of Zone M10 at only 0.10 my, it seems unnecessary to subdivide this biostratigraphic interval formally into two sub-zones. However, in areas where this biostratigraphic interval is expanded an informal subdivision into a lower Subzone a (*Globorotalia lobata/robusta-Globigerinoides subquadratus* Interval Range Subzone-Bolli's (1966) *Globigerinoides ruber* Zone) and upper Subzone b (*Globigerinoides subquadratus-Globoturboralita nepenthes* Interval Zone) may be appropriate.

M11. *Globoturboralita nepenthes/Neogloboquadrina mayeri* Concurrent Range Zone (M11; = Zone N14 of Blow, 1969, 1979)

Definition: Biostratigraphic interval with the concurrent range of the two nominate taxa from the FAD of *Globoturboralita nepenthes* (base) to the LAD of *Neogloboquadrina mayeri* (top)

Magnetostratigraphic calibration: Subchron C5r.3r-Subchron C5r.2r

Estimated age: 11.80–11.4 Ma; middle Miocene (Serravallian)

Remarks: The FAD of *Glb. nepenthes* has been calibrated to early Chron C5r in DSDP Holes 563 (Miller and others, 1985) and 608 (Miller and others, 1991) and occurs at approximately the same level in the Buff Bay section of Jamaica (Berggren, 1993) with an age estimate of 11.8 Ma, only ~0.1 my younger than the LAD of the *Gt. foehsi lobata/robusta* group. It would appear that this relatively brief temporal juxtaposition between the LAD of the *lobata/robusta* group and the FAD of *Glb. nepenthes* may explain the various records of overlap in the stratigraphic range of these two taxon groups in (relatively condensed) oceanic cores rather than diachrony. Determination of the FAD of *Glb. nepenthes* can also be a difficult taxonomic decision and requires high quality preservation. In Jamaica, the highest occurrence of *Gt. lobata/robusta* and the lowest occurrence of *Glb. nepenthes* are separated by a 22-m interval within which the LAD of *Gd. subquadratus* occurs approximately midway between these two events (Berggren, 1993).

M12. *Neogloboquadrina mayeri-Neogloboquadrina acostaensis* Interval Zone (M12; here defined; = N15 of Blow, 1969, 1979, but with different denotation)

Definition: Biostratigraphic interval between the LAD of *Neogloboquadrina mayeri* and the FAD of *Neogloboquadrina acostaensis*

Magnetostratigraphic calibration: Subchron C5r.2r-Subchron C5n.2n (early)

Estimated age: 11.4–10.9 Ma; middle-late Miocene (Serravallian-Tortonian)

Remarks: Bolli (1966) redefined earlier versions of this biostratigraphic interval as the *Globorotalia menardii* Interval Range Zone with the same boundary criteria used here and by Blow (1969, 1979) for his Zone N15. However in denoting it the *Globorotalia menardii* Zone becomes a partial, rather than an interval, range zone. Although *Gt. menardii* "A" (of Bolli) is often a common component of faunas of this biostratigraphic interval, we believe it more appropriate to denote this an interval range zone to free the zone from the burden of containing the nominate taxon (and because of continuing problems of mid-Miocene menardine taxonomy) in order that it be recognized (cf. Berggren, 1993, in which the name *Gt. menardii* "A" was used informally for this interval in a biostratigraphic study of Jamaica). Another taxon commonly occurring with *Gt. menardii* over this biostratigraphic interval is the distinctive *Gt. lengaensis*, which has its FAD near the FAD of *Glb. nepenthes* in Gulf Coast and Caribbean stratigraphic sections. At the same time, we have found the use of *Neogloboquadrina continuosa* as the nominate form of this biostratigraphic interval (Blow, 1969, 1979) unsatisfactory, inasmuch as that taxon is frequently absent or, at best, sporadic in many (sub)tropical late middle-early late Miocene stratigraphies including Jamaica (contra Blow, 1969, p. 248).

The LAD of *N. mayeri* in Jamaica is in an interval interpreted as Chron C5r.2r (= 11.4 Ma) and the FAD of *N. acostaensis* (interpreted as occurring in the *Globorotalia plesiotumida* Zone (= N17 of Blow, 1969, above an unconformity) is at least 45 m higher (Berggren, 1993). The duration of Zone M12 is estimated at ~0.5 my, and the zone is hereby reinstated in middle Miocene zonal nomenclature. The juxtaposition of these two datum events in North Atlantic DSDP Holes 558, 563 (Miller and others, 1985) and 608 (Miller and others, 1991) suggests the presence of a relatively brief early late Miocene hiatus in this region. The alternate interpretation of a later (diachronous) LAD of *N. mayeri* in mid-high latitudes is less appealing/parsimonious in view of the essentially (sub)tropical distribution of this taxon (see Miller and others, 1991, 1994, for additional discussion, and an alternate interpretation, based on integrated stable isotope-biostratigraphic correlations).

M13. *Neogloboquadrina acostaensis/Globorotalia lenguaensis* Concurrent Range Zone (M13; herein defined)

Definition: Biostratigraphic interval with the concurrent range of the nominate taxa between the FAD of *Neogloboquadrina acostaensis* and the LAD of *Globorotalia lenguaensis*

Magnetostratigraphic calibration: Subchron C5n.2n (early)-Subchron C3An.1n (inferred)

Estimated Age: 10.9–6.0 Ma; late Miocene (Tortonian-Messinian)

Remarks: We have found that both the initial evolutionary appearance of *Gt. plesiotumida* from its (putative) ancestor *Globorotalia merotumida* (=Zone N16/N17 boundary) (Blow, 1969, p. 52) and the initial appearance of *Neogloboquadrina*

humerosa (Bolli and Bermudez, 1965; Bolli and Saunders, 1985, p. 170) are difficult to apply as zonal criteria in the upper Miocene Series. The differing records of the FAD of *Gt. plesiotumida* in the literature attest to the difficulties in recognizing this taxon in both Atlantic and Indo-Pacific stratigraphies. Berggren (1993) drew attention to the difficulties encountered in distinguishing typical representatives of the predominantly Indo-Pacific *Gt. plesiotumida* group in late Miocene assemblages of the Atlantic-Caribbean region. On the other hand, we believe that the relatively small but morphologically distinct and geographically widespread taxon *Gt. lenguaensis* is an appropriate form for late Miocene biostratigraphy. Unfortunately, until recently, the only direct magnetostratigraphic calibration of the LAD of *Gt. lenguaensis* was that by Poore and others (1983, 1984) at the younger end of Chron C4An in DSDP Hole 519 (South Atlantic). However, Chaproniere and others (1994, Fig. 9) have calibrated this datum to the early part of Chronozone C3An.1n (6.0 Ma, this paper) in ODP Hole 840 (Tongan Platform). At this site, it occurs ~10 m below the FAD of *Pulleniatina primalis* and ~40 m above the FAD of *Globorotalia margaritae* which occurs within the upper third of Chronozone C3An.2n. Chaisson and Leckie (1993, Tables 1, 3) demonstrated that *Gt. lenguaensis* stratigraphically overlaps the lower part of the range of *Pu. primalis* in the uppermost Miocene of ODP Hole 806B (Ontong-Java Plateau) and that its LAD was ~5.5 Ma (using BKV85; = ~5.9 Ma in CK92 and 6.0 Ma in CK92/95 and this paper). This range is consistent with that delineated by Berggren (1977a) on the Rio Grande Rise (South Atlantic), although the uppermost part of the range of the taxon there may have been truncated by a regional unconformity (Hodell and Kennett, 1986; Aubry, pers. commun.). In Gulf of Mexico Eureka coreholes E66–73 and E68–136, the LAD of *Gt. lenguaensis* occurs virtually, and anomalously, at the same level as the FAD of *Gt. plesiotumida* and within Zone NN10 (i.e., ~8 Ma; Zhang and others, 1993; Aubry, 1993b).

We have placed the LAD of *Gt. lenguaensis* stratigraphically equivalent to the middle part of Chron C3An.1n (with an estimated age of 6.0 Ma) following Chaisson and Leckie (1993). Srinivasan and Kennett (1981b) subdivided this biostratigraphic interval (=Zone N17 of Blow, 1969, 1979) in the Indo-Pacific based on the FAD of the (geographically restricted) *Pulleniatina primalis*; Chaisson and Leckie (1993, Table 2) estimated this event to have occurred at 5.8 Ma (using BKV85; = 6.2 Ma in CK92; = 6.4 Ma in CK92/95 and this paper) in Hole 806B.

M13a. *Neogloboquadrina acostaensis-Globigerinoides extremus/Globorotalia plesiotumida* Interval Subzone (here defined; M13a)

Definition: Biostratigraphic interval between the FAD of *N. acostaensis* and the FAD of *Globigerinoides extremus* and/or *Globorotalia plesiotumida*

Magnetostratigraphic calibration: Subchron C5n.2n (early)-Subchron C4r.1n (estimated)

Estimate age: 10.9–8.3 Ma; late Miocene (Tortonian)

Remarks: The FAD of *Gt. plesiotumida* is difficult to determine under some circumstances owing to problems with general late Miocene menardine morphology and geographic distribution (predominantly an Indo-Pacific taxon; see discussion above). A common and geographically widely distributed late Neogene taxon (often associated with *Gt. plesiotumida*) is *Glo-*

bigerinoides extremus with its distinctly flattened (asymmetric) terminal chamber. This form is particularly well developed in the Mediterranean region where it appears together with another distinct form which is (apparently) restricted to the late Miocene (Messinian) *Turborotalita multiloba*.

Data relevant to determining the relationship of the FAD of *Gt. plesiotumida* and *Gl. extremus* include the following:

1. In Jamaica, the type level of the *Globorotalia plesiotumida* Zone is in Zone NN10 (Berggren, 1993) not in Zone NN11 (cf. Berggren and others 1983a; Aubry, 1993a) as previously thought (BKV85).
2. Backman and others (1990, p. 275) have provided new calibrations for the NN9/NN10 ($C4Ar = 9.20$ Ma in CK92 and 9.30 Ma in CK92/95) and NN10/NN11 ($C4r.1r = 8.10$ Ma in CK92 and 8.3 Ma in CK92/95 and this paper) zonal boundaries which means that Zone NN10 is ~ 1 my long.
3. Hodell and Kennett (1986, p. 294) provided a magneto-chronologic calibration of Chron 7N2 (=Chron C4n.2n) for the FAD of *Gt. plesiotumida* which corresponds to a level within Zone NN11, that appears too young based on evidence cited in points 1 and 2 above.
4. Chaisson and Leckie (1993) denote the FAD of *Gt. plesiotumida* and *Gd. extremus* within lower Zone NN11 and uppermost Zone NN10, respectively (Takayama, 1993, Table 12). The age of 7.1 Ma for the FAD of *Gt. plesiotumida* (BKF85) translates into 7.7 Ma (CK92/95 and this paper) and that of *Gd. extremus* to ~ 8.2 Ma (CK92/95 and this paper). At the same time, Chaisson and Leckie (1993, Table 1) extend questionable occurrences of *Gt. plesiotumida* as low as the basal part of 806B/31H (i.e., to about the same level as the FAD of *Gd. extremus* and within uppermost Zone NN10). However, the age estimates of the FAD of *Gd. extremus* and several other Neogene datums were incorrectly estimated by Chaisson and Leckie (1993, Table 3; see Table 13 of this paper for further explanation).
5. In Gulf of Mexico Eureka coreholes E66-73 and E68-136 as well as the Mt. Giammoia section (Sicily), the FAD of *Gd. extremus* is within Zone NN10 (WAB, unpubl. data), suggesting an age of 8.3 Ma (or older) for this datum.

We cite these data here by way of demonstrating a general consistency (at least in some instances) of the estimated FAD of *Gt. plesiotumida*, its close relationship with the FAD of *Gd. extremus*, and their possible use separately or together as sub-zonal indicators in upper Miocene (sub)tropical biostratigraphies under certain conditions. We have (somewhat arbitrarily) estimated the FAD of both *extremus* and *plesiotumida* at ~ 8.3 Ma (i.e., near or within Chron C4r.1n) in order to bring the FAD of *Gt. plesiotumida* in line with the general evidence reviewed above. Clearly additional verification of the FAD of these two Subzone M13a index taxa is needed.

While the study by Chaisson and Leckie (1993) suggests a short stratigraphic interval between the FADs of *Gd. extremus* and *Gt. plesiotumida*, their close juxtaposition in time suggests that either or both of these forms are appropriate as markers for subdivision of Zone M13 on a regional basis.

M13b. *Globigerinoides extremus/Globorotalia plesiotumida-Globorotalia lenguensis* Interval Subzone (M13b; here defined)

Definition: Biostratigraphic interval between the FAD of *Globigerinoides extremus* and/or *Globorotalia plesiotumida* and the LAD of *Globorotalia lenguensis*

Magnetochronologic calibration: Subchron C4r.1n (inferred)

Estimate age: 8.3–6.0 Ma

Remarks: See discussion above

M14. *Globorotalia lenguensis-Globorotalia tumida* Interval Zone (M14; here defined)

Definition: Biostratigraphic interval between the LAD of *Globorotalia lenguensis* and the FAD of *Globorotalia tumida*

Magnetochronologic calibration: Subchron C3An.1n (inferred)-Chron C3r (early Gilbert)

Estimated age: 6.0–5.6 Ma; latest Miocene (Messinian)

Remarks: The FAD of *Gt. tumida* has been substituted for the FAD of *Gt. margaritae* for the base of Zone P11 (see remarks under Zone P11 below) with the result that the M14/P11 zonal boundary corresponds closely to (but is somewhat older than) the base of the commonly accepted Miocene/Pliocene (Messinian/Zanclean) boundary with a revised age estimate of 5.32 Ma (Hilgen, 1991).

Pliocene zonation of (Sub)Tropical Regions.—The Pliocene P11-P16 zonal system of Berggren (1973, 1977a, b) was intended to serve as a zonation for Pliocene sediments of (predominantly) (sub)tropical-transitional areas of the Atlantic Ocean. Recent reviews by Weaver and Clement (1986, 1987) suggest that this zonal system is applicable with reasonable consistency to 41°–42° north latitude and our experience suggests comparable application in the South Atlantic. Farther to the north and south an alternative zonal scheme is necessary to reflect the provincial development of temperate taxa; this is discussed below. In fact, this zonation is equally adaptable to Indo-Pacific and Mediterranean stratigraphies with several shortcomings discussed below at appropriate places. In particular there are problems associated with the application of Zone P11 (as defined), which were recognized by the author shortly after its formulation. It was the critical examination of the biostratigraphic events of the upper Miocene-lower Pliocene interval by Hodell and Kennett (1986) that clarified the source of these problems. The reexamination conducted here of Neogene zonal schemes in connection with a revision of the Neogene time scale has afforded an opportunity of rectifying shortcomings in this, and other, zonal stratigraphies.

The P11-zonal scheme is discussed below and the zones redefined to conform with accepted and applied biostratigraphic concepts and terminology (see review by Schoch, 1989). Zone P16 is renamed and redefined for reasons given below.

P11. *Globorotalia tumida/Globoturborotalita nepenthes* Concurrent Range Zone (P11; herein redefined; emendation of Berggren, 1973, 1977b)

Definition: The biostratigraphic interval denoted by the concurrent range of the nominate taxa between the FAD of *Globorotalia tumida* and the LAD of *Globoturborotalita nepenthes*

Magnetochronologic calibration: Chron C3r (early Gilbert)-Subchron C3n.1n(y) (top Cochiti Subchron)

Estimated age: 5.6–4.18 Ma; early Pliocene (early Zanclean)

Remarks: Originally defined as the “concurrent range” of *Gl. margaritae* and *G. nepenthes* between the LAD of *Globoquadrigina dehiscens* and the LAD of *G. nepenthes*, this zone corresponded to a two-taxon partial range zone (see discussion in

Berggren and Miller, 1988, p. 364–367). Its redefinition here as a concurrent range zone with substitution of the FAD of *Gt. tumida* as the defining element of the base of the zone represents a return to the original intent/denotation of the zone (Berggren, 1973) and is consistent with appropriate and accepted stratigraphic usage. It also reflects recent data (Weaver and Clement, 1986, 1987; Hodell and Kennett, 1986) which suggest that *Gt. margaritae* has an erratic open ocean (non-Mediterranean) FAD spanning over 1 my from Chron C3An to basal Chron C3r (early Gilbert) which is lower (older) in some (sub)tropical stratigraphies of the western Pacific (DSDP Site 317, Manihiki Plateau; DSDP Site 588), Indian Ocean (DSDP Site 214, Ninety East Ridge) and the south equatorial Atlantic (DSDP Site 366, Sierra Leone Rise) than the LAD of *Gt. tumida* (Thunell, 1981; Hodell and Kennett, 1986). A brief overlap between the ranges of *Globoquadrina dehiscens* and *Gt. tumida* was observed only at DSDP Site 317 in the eastern equatorial Pacific (Thunell, 1981); indeed Hodell and Kennett (1986) have shown convincingly that the LAD of *Gl. dehiscens* had a diachronous span of ~1 my in the late Miocene Epoch, ranging from Chron C3Bn (~6.8 Ma; near the $\delta^{13}\text{C}$ shift) in subtropical regions to basal Chron C3r (early Gilbert; 5.5 Ma) in the tropics. At ODP Hole 806B, in which there is an expanded Miocene-Pliocene carbonate section, Chaisson and Leckie (1993) have observed a short (<3 m) overlap between *dehiscens* and *margaritae* at a level approximately coincident with the FAD of *Sphaeroidinella dehiscens* s.l. and ~5 m above the FAD of *Gt. tumida*. In view of the rather erratic FAD of *Gt. margaritae* and the fact that at SW Pacific DSDP Site 588 the FAD of *Gt. tumida* and *Gt. spherocomiozea* (used in SW Pacific biostratigraphies to denote the Miocene/Pliocene boundary) can be linked via strontium isotopes to a level near the base of the stratotype Zanclean in Sicily (Hodell and Kennett, 1986) at ~5.3 Ma (in the chronology of CK92; = 5.6 Ma in CK92/95 and this paper), the use of the FAD of *Gt. tumida* to denote the base of Zone P11 provides a means of regional correlation at a level close to, but slightly older than, the base of the Pliocene Epoch (as defined by the base of the Zanclean).

In the Mediterranean, the entry of *Gt. margaritae* was delayed by the reestablishment of normal marine conditions following the “terminal Miocene” desiccation phase. Although apparently present in rare numbers at the base of the Zanclean transgression a short distance/brief time below/before the Thvera (C3n.4n) Subchron, its lowest common occurrence (LCO) is normally associated with the Thvera (C3n.4n) Subchron (Channell and others, 1990; Langereis and Hilgen, 1991) with an estimated age of 5.2 Ma.

Thus it should be borne in mind that the co-occurrence of *Glb. nepenthes* and *Gt. margaritae* may serve as an approximation of Zone P11 equivalence (in predominantly subtropical stratigraphies) but may actually be somewhat older in some tropical areas. Under favorable circumstances, the FAD of *Sphaeroidinella dehiscens* sensu lato may serve to denote a level approximately equivalent to (but slightly younger than) the base of Zone P11.

P11a. *Globorotalia tumida/Globorotalia cibaoensis* Concurrent Range Subzone (P11a; Berggren, 1977b; herein redefined)

Definition: Biostratigraphic interval between the FAD of *Globorotalia tumida* and the LAD of *Globorotalia cibaoensis*

Magnetostratigraphic calibration: Chron C3r (early Gilbert)-Subchron C3n.2n (Nunivak Subchron)

Estimated age: 5.6–4.6 Ma; latest Miocene to early Pliocene (latest Messinian to early Zanclean)

Remarks: This subzone was originally denominated the *Globorotalia cibaoensis* Partial Range Zone, using as bracketing criteria the LAD of *Gg. dehiscens* (base) and FAD of *Globorotalia puncticulata* (top). The fact that as defined Subzone P11a did not correspond strictly to a partial range (sub)zone and that *Gt. puncticulata* does not (consistently) occur in lower Pliocene (sub)tropical stratigraphies lends a degree of urgency to the need for redefinition of this subzone. The essential ubiquity of *Gt. cibaoensis* in low latitude assemblages (Thunell, 1981) and its LAD concomitant with the FAD of *Gt. puncticulata* in transitional waters provides a means of correlation between low and mid-latitude biostratigraphies during the latest Miocene and earliest Pliocene Epochs. It should be noted that in its original definition, and as redefined here, Subzone P11a has a different (and more extensive) denotation than the *Gt. cibaoensis* Partial Range Zone of Thunell (1981, p. 82). The latter zone was defined as the partial range of the nominate taxon between the LAD of *Globoquadrina dehiscens* and the FAD of *Sphaeroidinella dehiscens* which is essentially correlative with Zone N18 of Blow (1969; but see discussion in Berggren, 1993, of problems with using Zone N18).

P11b. *Globorotalia cibaoensis-Globoturborotalita nepenthes* Interval Subzone (P11b + P11c combined; Berggren, 1977b; herein redefined)

Definition: Biostratigraphic interval between the LAD of *Globorotalia cibaoensis* and the LAD of *Globoturborotalita nepenthes*

Magnetostratigraphic calibration: Subchron 3n.2n (Ninuvak Subchron)-Subchron C3n.1n (late Cochiti Subchron)

Estimated age: 4.6–4.18 Ma; early Pliocene (early Zanclian)

Remarks: *Globorotalia puncticulata* and/or *Gt. crassaformis* are relatively common components of early Pliocene temperate areas (Berggren, 1977b; Keller, 1978, 1979a-c) but are absent, rare or delayed in most low-latitude areas (e.g., Gulf of Mexico, Keigwin, 1982; southern equatorial Atlantic and Indian Ocean, Thunell, 1981; Srinivasan and Chaturvedi, 1992) to levels close to, or slightly younger than, the LAD of *Glb. nepenthes* which has been correlated with the Cochiti Subchron. On the other hand, the FAD of *Gt. crassaformis* at cool subtropical South Atlantic Site 519 has been observed to occur in the lower part of Chron C3r (early Gilbert) prior to that of *Gt. puncticulata* which suggests that *crassaformis* may have evolved in the South Atlantic and migrated to lower latitudes in the early-mid Pliocene. In the Mediterranean, the initial appearance of *Gt. crassaformis* is associated with the Gilbert/Gauss boundary at ~3.55 Ma, over 1 my later than its earliest occurrence in temperate areas.

In its original definition, this biostratigraphic interval was subdivided into two subzones: a lower *Globorotalia puncticulata* Consecutive Range (=Lineage or Phylozone) Subzone (P11b) and an upper *Globorotalia crassaformis* sensu lato Consecutive Range Subzone (P11c) to denote the (interpreted) phylogenetic linkage between *Gt. cibaoensis* and *Gt. puncticulata*, and between *Gt. puncticulata* and *Gt. crassaformis*, respectively. In view of the continuing controversy over the ancestry

of *Gt. puncticulata* (Berggren, 1977b; Arnold, 1983 vs Wei, 1987; Scott, 1982) and *Gt. crassaformis* (Cifelli and Scott, 1986, p. 50), their essentially simultaneous FADs in some temperate stratigraphies (Keller, 1978, 1979a-c; Weaver and Clement, 1986, 1987; Scott and others, 1990) and the general absence or extreme rarity of *Gt. puncticulata* and/or *Gt. crassaformis* in lower Pliocene (sub)tropical assemblages it would seem more appropriate to simply use the LAD of the relatively ubiquitous (sub)tropical forms *Gt. cibaoensis* and *Glb. nepenthes* to denote the boundary between Subzones Pl1a/b and Pl2, respectively, and to designate this biostratigraphic interval as an interval zone, thus eliminating Subzone Pl1c from the (sub)tropical zonal scheme.

Pl2. *Globoturborotalita nepenthes-Globorotalia margaritae* Interval Zone (Pl2; herein redefined; emendation of Berggren, 1973; 1977b)

Definition: Biostratigraphic interval between the LAD of *Globoturborotalita nepenthes* and the LAD of *Globorotalia margaritae*

Magnetostratigraphic calibration: Subchron C3n.1n (late Cochiti Subchron)-Chron C2Ar(y) (Gauss/Gilbert boundary)

Estimated age: 4.18–3.58 Ma; early Pliocene (late Zanclean)

Remarks: Subzone Pl2 was originally designated the *Sphaeroidinellopsis subdehiscens-Globorotalia margaritae* Concurrent Range Zone (Berggren, 1973, 1977b) bracketed by the LAD of *Glb. nepenthes* (base) and the LAD of *Gt. margaritae* (top). As defined in this manner it corresponds, in fact, to a two-taxon Partial Range Zone (see discussion in Berggren and Miller, 1988). The zone is redefined here as interval range zone delimited by the LAD of two of the major and relatively ubiquitous (sub)tropical mid-Pliocene planktonic foraminiferal taxa.

Pl3. *Globorotalia margaritae-Sphaeroidinellopsis seminulina* Interval Zone (Pl3; herein redefined; emendation of Berggren, 1973, 1977b)

Definition: Biostratigraphic interval between the LAD of *Globorotalia margaritae* and the LAD of *Sphaeroidinellopsis seminulina*

Magnetostratigraphic calibration: Chron C2Ar(y) (Gauss/Gilbert boundary)-Subchron C2An.1r (earliest Kaena Subchron)

Estimated age: 3.58–3.12 Ma; late Pliocene (Piacenzian)

Remarks: Zone Pl3 was originally designated the *Globotruncana altispira-Sphaeroidinellopsis subdehiscens* Concurrent Range Zone (Berggren, 1973, 1977b) between the bracketing events of the LAD of *Gt. margaritae* (base) and the LAD of *Sphaeroidinellopsis subdehiscens* (top). As such it corresponded to a two-taxon partial range zone (see remarks above). It is here redefined as an interval range zone using two distinct and relatively ubiquitous (sub)tropical mid-Pliocene biostratigraphic events to denote its boundaries. The LAD of the *Globorotalia limbata* ecophenotypic variant *Globorotalia multicamerata* and the development of *S. dehiscens* sensu stricto (with everted test—encircling girdle) occurred in the upper part of this zone in tropical-subtropical regions. The change in *Sphaeroidinellopsis* taxonomy follows recent studies in that group (see discussion in Berggren, 1993).

Pl4. *Sphaeroidinellopsis seminulina-Dentoglobigerina altispira* Interval Zone (Pl4; herein redefined; emendation of Berggren, 1973, 1977b)

Definition: Biostratigraphic interval from the LAD of *Sphaeroidinellopsis seminulina* to the LAD of *Dentoglobigerina altispira*

Magnetostratigraphic calibration: Subchron C2An.1r (earliest Kaena Subchron)-Subchron C2An.1r (latest Kaena Subchron)

Estimated age: 3.12–3.09 Ma; late Pliocene (Piacenzian)

Remarks: Originally designated the *Gt. multicamerata-Globotruncana altispira* Concurrent Range Zone between the LAD of *Sphaeroidinellopsis subdehiscens* (base) and the virtually simultaneous LADs of the two nominate taxa (top), this zone as thus defined actually corresponds to a two-taxon partial range zone (see discussion in Berggren and Miller, 1988). As redefined here this extremely short (30 ky) zone characterizes a biostratigraphically distinct mid-Pliocene interval. In tropical-subtropical sequences, the FAD of *Globigerinoides fistulosus* is associated with the Kaena (C2An.1r) Subchron also.

Pl5. *Dentoglobigerina altispira-Globorotalia miocenica* Interval Zone (Pl5; herein redefined; emendation of Berggren, 1973, 1977b)

Definition: Biostratigraphic interval between the LAD of *Dentoglobigerina altispira* and the LAD of *Globorotalia miocenica*

Magnetostratigraphic calibration: Subchron C2An.1r (latest Kaena Subchron)-Subchron C2r.2r (early Matuyama; just prior to Reunion Subchron)

Estimated age: 3.09–2.30 Ma; late Pliocene (late Piacenzian)

Remarks: This zone was originally designated the *Globorotalia miocenica-Globorotalia exilis* Concurrent Zone delimited by the LAD of *Gg. altispira/Gt. multicamerata* (base) and the LAD of *Gt. miocenica* (top). As defined, it corresponded to a two taxon partial range zone and is redefined here as an interval range zone to conform to commonly accepted and applied biostratigraphic usage. A number of significant events characterize the stratigraphic interval delimited by the zonal boundary events: the LAD of *Globorotalia pertenuis* occurred in the latest part of the Gauss (2.63 Ma), the LAD of *Gt. puncticulata* occurred in temperate-subtropical regions of the Atlantic and Mediterranean in the early Matuyama (2.45 Ma), and *Pulleniatina* reappeared in the Atlantic Ocean (from the Indo-Pacific region) at the top of the zone after an approximately 1-my absence. This zone is applicable to Atlantic Ocean stratigraphy only inasmuch as *Gt. miocenica* (and *Globorotalia exilis*) are restricted to tropical-temperate regions of this ocean (Berggren, 1973, 1977a, b; Weaver and Clement, 1986, 1987). Alternative biostratigraphic zonal criteria for this interval suitable for Indo-Pacific stratigraphy are discussed below.

Pl6. *Globorotalia miocenica-Globigerinoides fistulosus* Interval Zone (Pl6; herein defined; modified from Berggren, 1973, 1977b)

Definition: Biostratigraphic interval from the LAD of *Globorotalia miocenica* to the LAD of *Globigerinoides fistulosus*

Magnetostratigraphic calibration: Subchron C2r.2r (early Matuyama; just below Reunion Subchron)-Chron C2n (latest Oloduvai Subchron)

Estimated age: 2.30–1.77 Ma; latest Pliocene (latest Piacenzian)

Remarks: The original definition of this zone, as the *Globigerinoides obliquus* Partial Range Zone between the LAD of *Gt. miocenica* (base) and the initial evolutionary appearance of

Globorotalia truncatulinoides (top), is redefined here to avoid the problems familiar to biostratigraphers of the ephemeral and quixotic FAD of *Gt. truncatulinoides* (Dowsett, 1988, 1990). The FAD of *Gt. truncatulinoides* has been recorded as early as the Subchron C2An.1n (Gauss) in the S. Equatorial Pacific (Dowsett, 1988, 1990), although in most subtropical regions of the Atlantic and Indo-Pacific Oceans, the FAD of *Gt. truncatulinoides* occurs generally just below the base of the Olduvai Subchron. It can also be (considerably) delayed in temperate-subantarctic regions. On the other hand, the LAD of *Globigerinoides extremus* has been reported at various levels ranging from just below the LAD of *Gt. miocenica* (early Matuyama, slightly older than the Reunion Subchron) (see discussion in Bolli and Saunders, 1985, relating to morphologic-taxonomic problems associated with recognition of *Gd. extremus*) to earliest to latest Olduvai Subchron. The latter level is taken as the true LAD of *Gd. extremus* (under ideal conditions). Srinivasan and Sinha (1992) have found that the LAD of *Gd. obliquus* sensu lato (= *Gd. extremus*) was diachronous between the SW Pacific (2.88 Ma; BKV85) and the Indian Ocean (1.8 Ma; BKV85). While this diachrony may be real, we suspect that this (apparent) diachrony is due, at least in part, to the inconsistent taxonomic usage referred to above. On the other hand, the LAD of *Gd. fistulosus* appears to be synchronous in the SW Pacific and Indian Oceans at the end of the Olduvai Subchron (Srinivasan and Sinha, 1992), consistent with its disappearance in the Atlantic (BKV85). For this reason, its LAD is used as the defining criterion for the top of Zone Pl6. The LAD of *Gd. extremus* and the FAD of *Gt. truncatulinoides* in (some) low latitude stratigraphies may serve to denote the uppermost part of Zone Pl6.

Late Pliocene zonation of the Indo-Pacific Region.—Following the closure of the Isthmus of Panama at ~3 Ma (Keigwin, 1982), planktonic foraminiferal faunas in the Atlantic and Indo-Pacific regions underwent a biogeographic provincialization that left its imprint on late Pliocene-Pleistocene faunas. Among the more characteristic features of the late Pliocene was the absence of typical Atlantic taxa *Gt. miocenica* and *Gt. exilis* in the Indo-Pacific region precluding their use in upper Pliocene (Zones Pl5 and Pl6) zonal stratigraphy there. However, alternate taxa (and zonal definitions) are suggested here following a discussion of some of the taxonomic problems that first require resolution.

Taxa that may serve as late Pliocene boundary criteria include *Globigerinoides fistulosus* and *Gt. pseudomiocenica*.

a. Jenkins and Orr (1972) proposed the *Globigerinoides fistulosus* Total Range Zone for late Pliocene tropical-subtropical stratigraphies of the eastern equatorial Pacific. This zone did not appear in subsequent (Jenkins and Srinivasan, 1986) late Neogene (sub)tropical zonal schemes nor did it figure in the tropical zonal scheme(s) adopted by Kennett and Srinivasan (1983). The magnetostratigraphically calibrated range of *Gd. fistulosus* is from the Mammoth (Subchron C2An.2r, or just below) to the top of the Olduvai Subchron (Chron C2n, or slightly above, i.e., ~3.33–1.56 Ma, using BKV85; = 3.58–1.70 Ma in CK92/95 and this paper). Srinivasan and Sinha (1992) have shown that the LAD of *Gd. extremus* is synchronous at the top of the Olduvai Subchron (C2n) in the Indian and SW Pacific Oceans. By contrast, Bolli and Premoli Silva (1973; see review in Bolli and Saunders, 1985) proposed a Pli-

ocene-Pleistocene zonal scheme for the Caribbean which included a “mid-Pliocene” *Globigerinoides trilobus fistulosus* Interval Range Subzone (of the *Gt. miocenica* Interval Range Zone) bracketed by the LAD of *Gt. margaritae evoluta* and the LAD of the nominate taxon. The LAD of *Gd. fistulosus* was shown to occur prior to that of *Gt. miocenica* and *Gt. exilis* coincident with the LAD of *Dentoglobigerina altispira* at ~2.8 Ma. A *Globorotalia exilis* Interval Subzone and *Globorotalia tosaensis* sensu stricto Interval Range Zone were inserted between the LAD of *Gd. fistulosus* and the FAD of *Gt. truncatulinoides* in this Caribbean zonation. On the other hand, Keigwin (1982) showed that *Gd. fistulosus* overlapped with *Gt. miocenica* and *Gt. exilis* at DSDP Site 502 (Colombia Basin) and overlapped with *Gt. truncatulinoides* at eastern tropical Pacific Site 503. This apparent discrepancy has its explanation in the fact that Bolli and Premoli Silva (1973) restricted their concept of the taxon *fistulosus* sensu stricto to forms on which the bizarre arborescent, staghorn and cockscomb ornament is developed on the chambers of the last whorl, while reserving the appellation *Globigerinoides trilobus cf. fistulosus* for presumably latest Pliocene forms with reduced chamber ornament generally restricted to the last chamber. However, most workers would include all fistulose forms in *fistulosus* sensu stricto, and indeed, Kennett and Srinivasan (1983, Plate 14, Figs. 7–9) illustrate fully fistulose forms from the early Pleistocene *Gl. tosaensis*-*Gt. truncatulinoides* “overlap” (= Interval) Range Zone. A similar overlap has been demonstrated in west equatorial Pacific ODP Site 806 (Chaisson and Leckie, 1993) just above the LAD of *Discoaster brouweri* (Takayama, 1993).

b. The taxon *Gt. pseudomiocenica*, the ancestor of *Gt. miocenica* in the Atlantic Ocean, occurs in Pliocene faunas of the Indo-Pacific region. It was recorded by Keigwin (1982) as part of the *Gt. menardii* sensu lato group in the Gulf of Mexico and eastern equatorial Pacific and by Jenkins and Orr (1972, Plate 23, Figs. 1–3, 7–9; cf. Bolli and Saunders, 1985, Fig. 35, 1–3 of *Gt. pseudomiocenica*) as *Gt. exilis* in the eastern equatorial Pacific. In the Red Sea, Fleisher (1974, Plate 21, Figs. 1–4) recorded *pseudomiocenica* as *Globorotalia* sp. cf. *praemiocenica*. Together with other records from DSDP and ODP cruises in which *Gt. pseudomiocenica* is couched in other menardine taxonomies, these records indicate that *pseudomiocenica* had an extensive geographic distribution in the Indo-Pacific region during the Pliocene Epoch. Fleisher (1974) recorded *Gt. praemiocenica* (= *pseudomiocenica*) from the late Pliocene *Globigerinoides ruber* Assemblage Zone of the Arabian Sea. Jenkins and Orr (1972, p. 1098) indicated that “*exilis*” (= *pseudomiocenica*) was predominantly dextrally coiled and that its extinction denoted a “relatively consistent datum in the *G. fistulosus* Zone”. These observations are consistent with a study by Berggren (unpubl. data) of the stratigraphic range of the *Gt. miocenica*-*pseudomiocenica* group at DSDP Sites 502 and 503. While the evolutionary transition from *Gt. pseudomiocenica* to *Gt. miocenica* can be observed from Chron C2An.3n to C2An.2n (early to middle Gauss) at DSDP Site 502 (Colombia Basin), *Gt. pseudomiocenica* continued at DSDP Site 503 (eastern equatorial Pacific) until Chron C2r.2r (early Matuyama) and had its LAD at essentially the same stratigraphic level as *Gt. miocenica* in the Atlantic-Caribbean region (i.e., 2.30 Ma). It is dextrally coiled from the late Gilbert (just below the Cochiti Subchron; Chron C3n.1n) to its extinction in the early Matu-

yama, similar to its coiling pattern at Site 502 except that at the latter site the dextral coiling pattern began during the Thvera Subchron (Subchron C3n.4n).

This review indicates that the taxa *fistulosus* and *pseudomicenica* were extensively distributed in the Indo-Pacific during the late Pliocene and suitable for substitution for boundary definition and/or characterization of upper Pliocene Zones PL5 and PL6 in these regions with the caveat that *fistulosus* is restricted to tropical-subtropical regions and less applicable to temperate regions.

PL5. *Dentoglobigerina altispira-Globorotalia pseudomiocenica* Interval Zone (Zone PL5; Indo-Pacific; here defined)

Definition: Biostratigraphic interval from the LAD of *Dentoglobigerina altispira* to the LAD of *Globorotalia pseudomiocenica*

Magnetostratigraphic calibration: Subchron C2An.1r (Kaena Subchron)-Subchron C2r.2r (early Matuyama)

Estimated age: 3.09–2.30 Ma; late Pliocene (late Piacenzian)

Remarks: As defined here Zone PL5 in the Indo-Pacific has the same temporal extent as Zone PL5 of the Atlantic-Caribbean region; see further discussion above.

PL6. *Globorotalia pseudomiocenica-Globigerinoides fistulosus* Interval Zone (PL6; Indo-Pacific; here defined)

Definition: Biostratigraphic interval from LAD of *Globorotalia pseudomiocenica* to the LAD of *Globigerinoides fistulosus*

Magnetostratigraphic calibration: Subchron C2r.2r (early Matuyama)-Chron C2n (latest Olduvai)

Estimated age: 2.30–1.77 Ma; latest Pliocene (latest Piacenzian)

Remarks: As defined here this zone has the same temporal duration as Zone PL6 of the Atlantic-Caribbean region. The range of *Globigerinoides fistulosus* is essentially concomitant with the combined interval of Zones PL5 and PL6 and may serve as an adjunct/substitute for recognizing part/all of this biostratigraphic interval in the absence of one or the other of the boundary denominating taxa. For further discussion see above.

Pleistocene Zonation of (Sub)Tropical Regions.—The inadequacy of Blow's (1969, 1979) Pleistocene Zone N23 was already pointed out by Bronnimann and Resig (1971, p. 1248) based on the general absence of *Sphaerodinella dehiscens excavata* in bottom samples in the vicinity of DSDP Leg 7 sites in the equatorial Pacific and on the subjectivity involved in distinguishing clearly between *Globigerina* (*vel* *Bolliella*) *calida calida* and *B. calida praecalida* (see also Bolli and Saunders, 1985, p. 176, who noted its (?local) late Pleistocene FAD in the Caribbean-Atlantic region while referring to its apparently sporadic and restricted occurrence in the early Pliocene Epoch of the Indo-Pacific). Chaproniere and others (1994) have recently correlated this event to the late Brunhes (Chron C1n) oxygen isotope stage 7 (~0.22 Ma). Bronnimann and Resig (1971) suggested substituting the FAD of *Hastigerinella adamsi* as the denominative form for a formally defined Zone N23 but were unable to provide an estimated age for this datum event, and it remains uncalibrated to either stable isotope stratigraphic zones or paleomagnetic stratigraphy to this date. The recent discovery that the FAD of *Gt. truncatulinoides* in the southeast Pacific is at the late Pliocene Gauss/Matuyama (Chron C2r/C2An) boundary with an estimated age of 2.581 Ma (Jenkins and Gamson, 1993; Langereis and others, 1994; this paper) renders Zone

N22 as defined by Blow (1969) difficult to apply globally, because in the southern hemisphere it overlaps with the upper part of Zone PL5 and basal PL6. Its use as a partial range or interval zone (with a different definition for its base) could be justified, and we have used the latter course in (re)defining the N22 and N23 zonal interval. We recognize but a single zone in the Pleistocene (with two subzones; Fig. 6) and designate it as Pt1 (with the Pt standing for Pleistocene in the same manner that Pl refers to the Pliocene; see above). More detailed biostratigraphic/biochronologic resolution in the Pleistocene is best achieved by using repetitive/cyclical/periodic changes such as coiling changes, (local to regional) climatically controlled taxon entries/disappearance and other local zonations.

The chronology of Pleistocene (sub)tropical planktonic foraminiferal datum events/zones is shown in Figure 13.

Pt1. *Globigerinoides fistulosus-Globorotalia truncatulinoides* Interval Zone (Pt 1; herein defined)

Definition: Biostratigraphic interval characterized by *Globorotalia truncatulinoides* between the LAD of *Globigerinoides fistulosus* and the present day

Magnetostratigraphic calibration: Chron C2n (Olduvai Subchron)-present day

Estimated age: 1.77 Ma to present time; Pleistocene (including Holocene)

Remarks: The LAD of *Globigerinoides fistulosus* has been found to occur at the top of the Olduvai (C2n) Subchron in both Atlantic and Pacific (sub)tropical sites at ~1.77 Ma. *Gt. truncatulinoides*

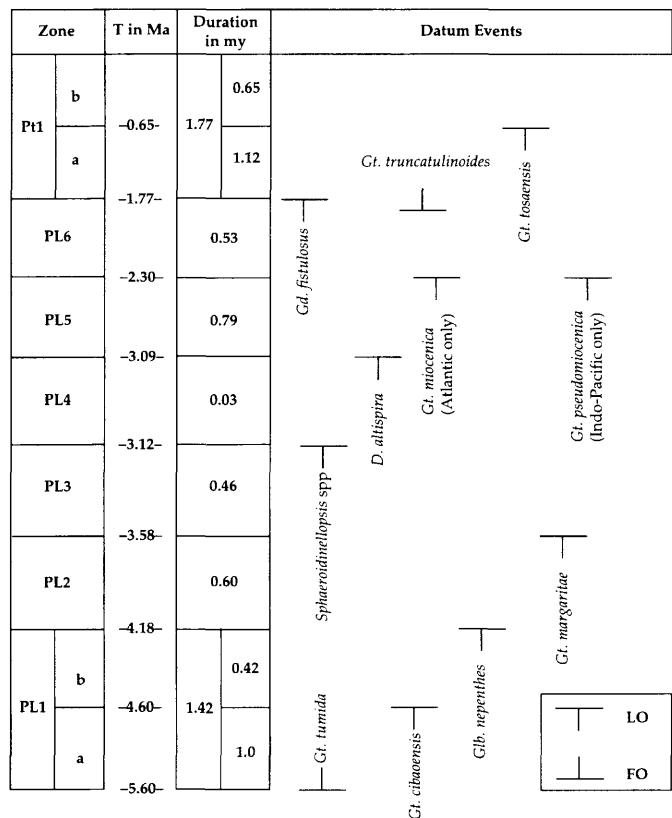


FIG. 13.—Chronology of Pliocene-Pleistocene (sub)tropical planktonic foraminiferal zones.

catulinoides characteristically appeared in northern hemisphere (sub)tropical and transitional geographies near the Chron C2n/C2r boundary (~2 Ma) and is a widespread element in Pleistocene faunas.

Pt1a. *Globigerinoides fistulosus-Globorotalia tosaensis* Interval Subzone (Pt1a; herein defined)

Definition: Biostratigraphic interval between the LAD of *Globigerinoides fistulosus* and the LAD of *Globorotalia tosaensis*

Magnetostratigraphically calibrated range: Chron C2n (Olduvai Subchron)-Chron C1n (early Brunhes)

Estimated age: 1.77–0.65 Ma; early to earliest middle Pleistocene

Remarks: The early/middle Pleistocene LAD of *Gt. tosaensis* is used as the denotative criterion for this subzone. The association of *Gt. tosaensis* and its descendant *Gt. truncatulinoides* following the FAD of the latter was used to denote a (predominantly) lower Pleistocene cool subtropical-temperate zone by Srinivasan and Kennett (1981b).

Pt1b. *Globorotalia truncatulinoides* Partial Range Subzone (Pt1b; Srinivasan and Kennett, 1981b)

Definition: Biostratigraphic interval characterized by the partial range of the nominate taxon following the LAD of *Globorotalia tosaensis*

Magnetostratigraphically calibrated range: Chron C1n to present day (early-late Brunhes)

Estimated age: 0.65 Ma to present time; early Pleistocene-Holocene

Remarks: We use this subzone in the same sense as that defined by Srinivasan and Kennett (1981b). Subdivision of the middle and late Pleistocene Period may be achieved by using several “datum events” recently calibrated to the magnetochronologic scale as a result of ODP drilling in the Atlantic and Indo-Pacific oceans, although the use of some of these events may require further verification in different biogeographies.

Miocene Zonation of Temperate-Transitional Regions.—Miocene temperate-transitional planktonic foraminiferal zonal schemes have been developed for the Indo-Pacific region by Jenkins (1967, 1975), Srinivasan and Kennett (1981a, b), Kennett and Srinivasan (1983); by Berggren (1973, 1977a, b, 1992) and Berggren and others (1983a) predominantly for Southern Hemisphere (predominantly Atlantic) stratigraphies, whereas Northern Hemisphere zonal stratigraphies have been developed/discussed by, among others, Berggren (1972) and Poore and Berggren (1975) for the North Atlantic, and Keller (1979a-c, 1980a, b, 1981) for the North Pacific. In this section, we have attempted to combine elements of these biostratigraphic schemes into a unified zonation which is broadly applicable over most of these areas. The notation Mt is used to denote application to temperate-transitional regions; the notation M was used earlier by Berggren (1977b) for this zonal scheme.

Mt1. *Globorotalia kugleri* Total Range Zone (Bolli, 1957b; Mt1; Berggren in Berggren and others, 1983a; =N4 of Berggren and Miller, 1988)

Definition: Total range of the nominate taxon

Magnetochronologic calibration: Subchron C6Cn.2n(o)-Chron C6Ar (mid)

Estimated Age: 23.8–21.5 Ma; early Aquitanian

Remarks: This zone (and its subzonal subdivision) is the same as the *Gt. kugleri* Total Range Zone (M1) described above under the (sub)tropical region(s) inasmuch as the nominate taxon(a) of the (sub)zones have been found to occur in temperate-transitional areas as well (see also Srinivasan and Kennett, 1981a, b; Kennett and Srinivasan, 1983, 1984). Further details on this zone are provided under the description of this zone in the section on (sub)tropical zones described above.

Mt2. *Globorotalia incognita/Globorotalia semivera* Partial Range Zone (Mt2; Berggren, in Berggren and others, 1983a)

Definition: The partial range of the nominate taxa between the LAD of *Globorotalia kugleri* and the FAD of *Globorotalia praescitula*

Magnetochronologic calibration: Chron C6Ar (mid)-Chron C5En (mid)

Estimated age: 21.5–18.5 Ma; early Miocene (Burdigalian)

Remarks: The FAD of *Gt. praescitula* has been calibrated to mid-Chron C5En at North Atlantic (42°N) DSDP Site 608 (Miller and others, 1991) and Southern Indian Ocean-Subantarctic (58°S) ODP Sites 748 and 751 (Berggren, 1992) providing a reliable, regional magnetobiostratigraphic correlation datum.

Mt3. *Globorotalia praescitula-Globorotalia miozea* Interval Zone (Mt3; herein redefined from Berggren, 1992, as informal zone NK2 of Kerguelen Plateau)

Definition: Biostratigraphic interval between the FAD of the nominate taxon to the FAD of its descendant *Globorotalia miozea*

Magnetochronologic calibration: Chron C5En (mid)-Chron C5Cn.3n (early)

Estimated age: 18.5–16.7 Ma; early Miocene (Burdigalian)

Remarks: This zone was originally defined (informally) in the subantarctic region of the southern Indian Ocean (Berggren, 1992). The widespread occurrence of both of the nominate taxa in transitional and subantarctic biostratigraphies make them suitable as zonal boundary markers and as defined here the zone corresponds exactly with (informal) zone AN3 (see below) of the Subantarctic region. This zone corresponds in part to the *Globorotalia zealandica-Globorotalia pseudomiozea* (M3) Zone of the South Atlantic (Berggren, 1977a) whose base was correlated with a level within Chron C5Dn. However, continuing problems with determining the precise relationships between, and the sequential appearance of *Gt. zealandica* and *Gt. praescitula* (see Scott and others, 1990) have led us to abandon that zone in favor of a zone based on the less equivocal FAD of *G. praescitula*.

Mt4. *Globorotalia miozea* Partial Range Zone (Mt4; =Zone M4 of Berggren, 1977b)

Definition: Biostratigraphic interval between the FAD of *Globorotalia miozea* and the FAD of *Praeorbulina sicana*

Magnetochronologic calibration: Subchron C5Cn.3n (early)-Subchron C5Cn.2n

Estimated age: 16.7–16.4 Ma; latest early Miocene (latest Burdigalian)

Remarks: This zone is retained as originally defined (Berggren, 1977b) as the partial range of *miozea* between its FAD and that of *sicana*. This zone corresponds to temperate/transitional Zone M4 of Berggren (1977b) and to the *Globigerinoides*

bisphericus Partial Range Subzone (M4b) of (sub)tropical regions (= upper part of Zone N7 of Blow, 1969, 1979).

Mt5. *Praeorbulina sicana-Orbulina suturalis* Interval Zone (Mt5; = combined Zones M5 and M6 of Berggren, 1977b)

Definition: Biostratigraphic interval between the FAD of *Praeorbulina sicana* and the FAD of *Orbulina suturalis*

Magnetostratigraphic calibration: Subchron C5Cn.2n-Subchron C5Bn.2n

Estimated age: 16.4–15.1 Ma; middle Miocene (Langhian)

Remarks: This zone corresponds to Zones M5 and M6 of Berggren (1977b) of the temperate/transitional regions and to Zone M5 of (sub)tropical regions (= Zone N8 of Blow, 1969, 1979). Considering the relatively brief interval between the estimated ages of the FAD of *Pr. sicana* (16.4 Ma) and the FAD of *Pr. glomerosa* (16.1 Ma), recognition of these discrete biostratigraphic events may not be uniformly possible. For those instances where they are, we propose a two-fold subdivision of this biostratigraphical interval identical to the (sub)tropical regions.

Mt5a. *Praeorbulina sicana-Praeorbulina glomerosa glomerosa* Interval Subzone (Mt5a; = Zone M5 of Berggren, 1977b, emended)

Definition: Biostratigraphic interval between the FAD of *Praeorbulina sicana* and the FAD of *Praeorbulina glomerosa glomerosa*

Magnetostratigraphic calibration: Subchron C5Cn.2n-Subchron C5Cn.1n

Estimated age: 16.4–16.1 Ma; earliest middle Miocene (earliest Langhian)

Remarks: As originally defined (Berggren, 1977b), this (sub)zone represented the partial range of two taxa: *Pr. sicana* and *Gt. miozea* between the FAD of *sicana* and the FAD of *glomerosa* sensu stricto. We restrict this here simply to the interval between the same criteria.

This subzone is correlative with and identical to Subzone M5a (*Pr. sicana*—*Pr. glomerosa glomerosa* Interval Range Subzone) of the (sub)tropical region (= upper part of Zone N8 of Blow, 1969, 1979) (see above).

Mt5b. *Praeorbulina glomerosa glomerosa-Orbulina suturalis* Interval Subzone (Mt5b; = emendation of Zone M6 of Berggren, 1977b)

Definition: Biostratigraphic interval between the FAD of *Praeorbulina glomerosa glomerosa* and the FAD of *Orbulina suturalis*

Magnetostratigraphic calibration: Subchron C5Cn.1n-Subchron C5Bn.2n

Estimated age: 16.1–15.1 Ma; middle Miocene (Langhian)

Remarks: As originally defined (Berggren, 1977b) with the same bounding criteria this was a partial range zone of two taxa: *Pr. sicana* and *Pr. glomerosa glomerosa*. It is emended here to an (more appropriate) interval range subzone. This zone corresponds precisely to (sub)tropical Subzone M5b (see above) and is correlative with Zone M6 of Berggren (1977b) and the upper part of Zone N8 (Blow, 1969, 1979). The occurrence of the praeorbulinid-orbulinid bioseries at relatively high latitudes reflects the global warming trend (and expansion of low latitude warm water masses) during the latest early and earliest middle Miocene.

Mt6. *Orbulina suturalis/Globorotalia peripheroronda* Concurrent Range Zone (Mt6; = Zone M7 of Berggren, 1977b)

Definition: Concurrent range of the nominate taxa between the FAD of *Orbulina suturalis* and the LAD of *Globorotalia peripheroronda*

Magnetostratigraphic calibration: Subchron C5Bn.2n-Chron C5ACn (estimated)

Estimated age: 15.1–14.0 Ma; middle Miocene (latest Langhian-early Serravallian)

Remarks: The LAD of *Gt. peripheroronda* is estimated here to correspond to Chron C5ACn (in the absence of a direct magnetostratigraphic correlation) based on the observed overlap in the stratigraphic ranges of *Gt. peripheroronda* and *Gt. peripheracuta* (Bolli and Saunders, 1985; pers. observ., WAB) and the fact that the FAD of the latter taxon is calibrated to Chron C5Bn(y). The Mt6/Mt7 zonal boundary is thus somewhat stratigraphically higher (younger) than the (sub)tropical M5/M6 zonal boundary.

Mt7. *Globorotalia peripheroronda-Globoturboralita nepenthes* Interval Zone (Mt7; here defined)

Definition: Biostratigraphic interval from LAD of *Globorotalia peripheroronda* to the FAD of *Globoturboralita nepenthes*

Magnetostratigraphic calibration: Chron C5ACn (estimated)-Subchron C5r.3r

Estimated age: 14.0–11.8 Ma; middle Miocene (Serravallian)

Remarks: This biostratigraphic interval corresponds to the *Globigerina druryi* (M8) Partial Range Zone of Berggren (1977b) and is characterized by the (sporadic) presence of that taxon, *Globoturboralita decoraperta*, *Globigerina woodi*, *Neogloboquadrina mayeri* and the presence of, and transition between, *Globorotalia miozea* and *Globorotalia conoidea*, among others. In view of the sporadic occurrence of *G. druryi* in this interval, it is thought more appropriate to designate this an interval range zone.

Mt8. *Globoturboralita nepenthes/Neogloboquadrina mayeri* Concurrent Range Zone (Mt 8; = Zone N14 of Blow, 1969, 1979)

Definition: Concurrent range of the nominate taxa between the FAD of *Globoturboralita nepenthes* and the LAD of *Neogloboquadrina mayeri*

Magnetostratigraphic calibration: Subchron C5r.3r-Subchron C5r.2r

Estimated age: 11.8–11.4 Ma; middle Miocene (Serravallian)

Remarks: This zone is generally applicable to (sub)tropical and transitional biostratigraphies, although the lowest (earliest) occurrence of *Glb. nepenthes* may be delayed in some localities (e.g., Srinivasan and Kennett, 1981b). Miller and others (1994) argue that the LAD of *N. mayeri* is latitudinally diachronous, persisting to the earliest part of Chron C5n at mid-latitudes (DSDP Site 563, among others), in the North Atlantic, although an unconformity at this (and other localities) could equally well have juxtaposed the LAD of *N. mayeri* and FAD of *N. acostaensis* (Aubry, 1993a; Berggren, 1993).

Mt9. *Neogloboquadrina mayeri-Globorotalia conomiozea* Interval Zone herein defined; Mt9)

Definition: Biostratigraphic interval between the LAD of *Neogloboquadrina mayeri* and the FAD of *Globorotalia conomiozea*

Magnetostratigraphic calibration: Subchron C5r.1r-Subchron C3Br.1r

Estimated age: 11.4–7.12 Ma; latest middle to earliest late Miocene (latest Serravallian-earliest Messinian)

Remarks: The rarity or absence of *N. acostaensis* in transitional biostratigraphies precludes its application outside of (sub)tropical regions. There have been numerous attempts at zonation of the upper Miocene Series of temperate-cool subtropical regions. Kennett (1973) used the sequential partial ranges of *Neogloboquadrina continuosa*, *Glb. nepenthes* and *Gt. conomiozea* following the extinction of *N. mayeri* in the Southwest Pacific, while Jenkins (1967, 1971, 1975, 1993a) and Berggren (1977a; Berggren and others, 1983a) and Poore and Berggren (1975) utilized the presence of members of the *Gt. miotumida* (including *Gt. conoidea*-*Gt. conomiozea* complex in developing an upper Miocene zonation applicable to the Southwest Pacific, South Atlantic and North Atlantic, respectively. We retain these forms as definitive and denotative of two upper Miocene zones which would appear to find application in both northern and southern ocean late Miocene biogeographies. Characteristic elements of this biostratigraphic interval include, among others, *Glb. nepenthes*, *Gl. woodi*, *Gt. conoidea*, *Gt. lengaensis*, *Gt. menardii* sensu lato, *Gt. scitula* and *Neogloboquadrina nympha* (a transitional-subantarctic isomorph of *N. acostaensis* having a considerably earlier FAD than *N. acostaensis*). This zone corresponds to the *Globorotalia miotumida* Zone of Jenkins (1967, et seq.) and to the *Globorotalia paralengaensis*-*Neogloboquadrina continuosa* (M10) Partial Range Zone and the succeeding *Globorotalia miozea*-*Globorotalia conoidea* (M11) Partial Range Zone (Berggren, 1977a, b) which used the FAD of *N. acostaensis* as the defining criterion separating the two at DSDP Site 516. The Rio Grande Rise is located in a region which was alternately influenced by subtropical and transitional waters which accounts for the alternating presence of (subtropical) elements as the *fohsii* group and the *miozea*-*conoidea*-*conomiozea* group (Berggren and others, 1983a). *Globorotalia paralengaensis* is now included in the concept of *Gt. lengaensis* and the sporadic distribution (and apparently premature LAD) of this taxon and of *N. acostaensis* in transitional biostratigraphies suggests that a more appropriate zonation be found for this interval.

Mt10. *Globorotalia conomiozea*/*Globorotalia mediterranea*-*Globorotalia sphericomiozea* Interval Zone (Mt10; here defined)

Definition: Biostratigraphic interval between the FAD of *Globorotalia conomiozea* and/or *Globorotalia mediterranea* and the FAD of *Globorotalia sphericomiozea*

Magnetostratigraphic calibration: Subchron C3Br.1r-Chron C3r (mid)

Estimated age: 7.12–5.6 Ma; late Miocene (Messinian)

Remarks: The review by Hodell and Kennett (1986) suggests that the FAD of *G. conomiozea* (as morphometrically distinguished from its sister taxon/ancestor *Gt. conoidea* by Malmgren and Kennett, 1982; cf. Scott and others, 1990) occurred in Subchron 5n.1r (BKV85; = Subchron C3An.1r of CK92/95) at South Atlantic DSDP Site 588 which appears at first glance to have been consistent with the record in Subchron C3An.1r in Crete by Langereis and others, 1984; cf. BKVC85) which is above the Chron 6 (=Chron C3Ar) carbon isotope shift of Haq

and others (1980). On the other hand, a somewhat earlier initial occurrence of *Gt. conomiozea* was recorded by Kennett and Watkins (1974) in the Blind River section of New Zealand within Subchron 6.1r (=Chron C3Ar) coincident with the carbon shift (see also Loutit and Kennett, 1979; Kennett and Srinivasan, 1984; cf. recently revised magnetobiostratigraphic interpretation by Roberts and others, 1994, of the Blind River section which suggests a local FAD of *conomiozea* in Subchron C3An.1r, at ~6.2 Ma in the chronology of CK92/95 and this paper). In view of the fact that the earliest occurrence of this taxon has been used to denote the base of the Messinian Stage in the Mediterranean, this point assumes a significance beyond mere provincial correlation. The recent modification to the GPTS by Cande and Kent (1992; 1995 and this paper) shows that the earlier Chron 6 (in BKV85; = Chron C3Ar to Chron C3Br of this paper) contains two additional normal subchrons which now allows an unambiguous correlation of the FAD of *conomiozea* in the Cretan sections to the new GPTS in Subchron C3Br.1r (inadvertently attributed to Chron C3Bn.1r in Krijgsman and others, 1994) with an estimated age of 6.92 Ma in CK92 and 7.12 Ma in the chronology adopted here. The FAD of *Gt. conomiozea*, nominate taxon for the boundary between Zones Mt10 and Mt11, is correlated with Subchron C3Br.1r at 7.12 Ma and equated with the Tortonian/Messinian boundary.

The initial appearance of *Globorotalia sphericomiozea* at transitional South Atlantic DSDP Site 588 has been found to coincide with that of *Gt. tumida* (Hodell and Kennett, 1986) and to be only nominally younger than its FAD at more southerly DSDP Sites 590 and 284. We have also observed this form (i.e., *sphericomiozea*) in high southern latitude ODP Site 747 at about the same level (Berggren, 1992). This zone corresponds closely to the *Globorotalia conomiozea*-*Globorotalia mediterranea* (M12) Partial Range Zone (Berggren, 1977a, b) which used the FAD of *Gt. cibaoensis* as its upper boundary. However, it would appear that the FAD of *Gt. cibaoensis* is somewhat older than that suggested by Berggren (1977a, b) on the Rio Grande Rise, thus necessitating a revised definition of this zone. This zone corresponds (in greater part but not in its entirety) to the *Gt. conomiozea* Zone of Jenkins (1971, et seq.) and Kennett (1973).

The chronology of early and middle-late Miocene transitional planktonic foraminiferal datum events/zones is shown in Figures 14 and 15, respectively.

Pliocene-Pleistocene Zonation of North Atlantic Temperate Region.—Weaver and Clement (1986, 1987) have reviewed the historical development of temperate-subarctic late Neogene planktonic foraminiferal zonal schemes from Berggren (1972) through the studies of Poore and Berggren (1974, 1975) and assessed these zones in terms of paleomagnetic calibrations made possible by North Atlantic DSDP Leg 94. Elements of the PI zonation of Berggren (1973, 1977b) were retained for the lower Pliocene Series, but for the mid-upper Pliocene Series, other taxa were used to reflect the biogeographic differentiation which occurred as a result of significant high-latitude cooling. This zonal scheme is adopted here for temperate-subantarctic stratigraphies of the North Atlantic. It should be pointed out in passing that the zones of Weaver and Clement (1986) are interval (rather than partial) range zones as defined by the ISSC (Hedberg, 1976; recently revised in Salvador, 1994).

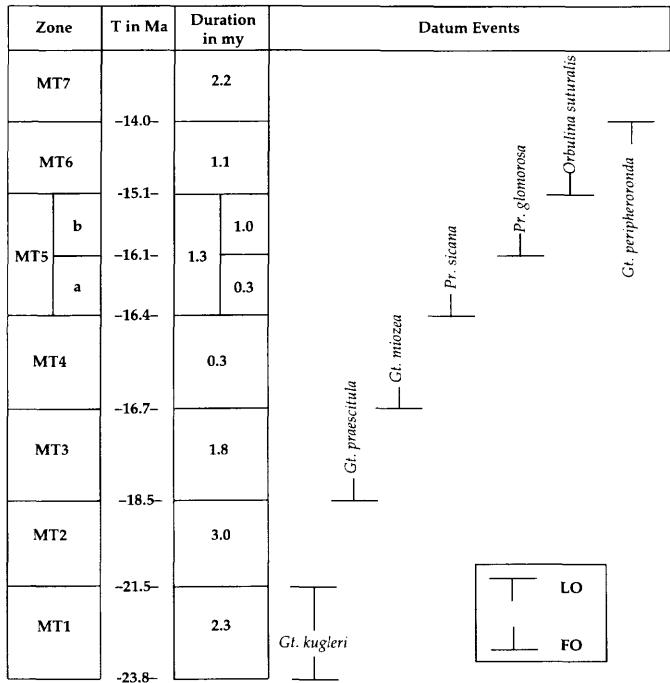


FIG. 14.—Chronology of early Miocene transitional planktonic foraminiferal zones.

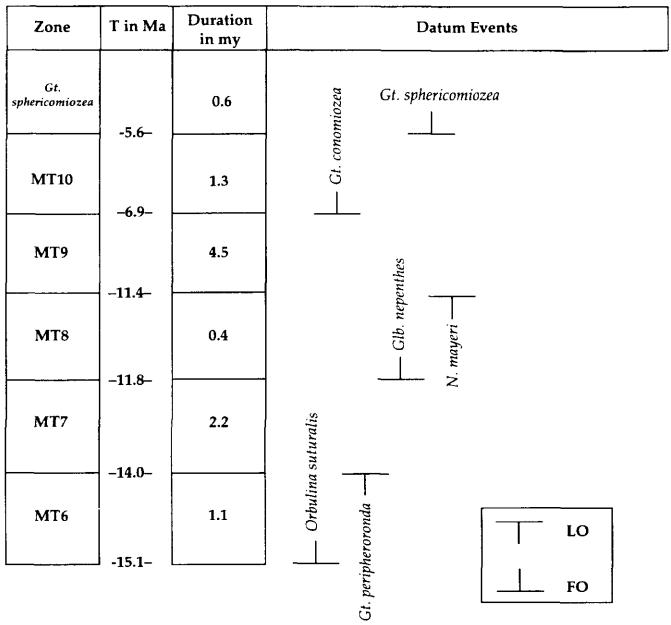


FIG. 15.—Chronology of middle and late Miocene transitional planktonic foraminiferal zones.

Pliocene-Pleistocene Zonation of Transitional Austral (Southern Hemisphere) Regions.—The zonal scheme of Kennett (1973) and Srinivasan and Kennett (1981a, b) is used for late Neogene (Pliocene-Pleistocene) transitional biostratigraphies. Jenkins (1993a) has recently presented a review of mid- and high-latitude planktonic foraminiferal biostratigraphy of this region.

Neogene zonation of Austral-(Sub)Antarctic Regions.—A seven-fold Neogene biostratigraphic zonation was developed for the austral-subantarctic region of the Kerguelen Plateau (Berggren, 1992; see also Jenkins, 1993a). Correlation of Zones An1–4 (lower to lower middle Miocene) with contemporary temperate-transitional biostratigraphies is relatively straightforward owing to comparable (if fewer) elements in common between the two regions and direct, independent, magnetostratigraphic correlation in both cases. With increased middle Miocene high-latitude cooling, faunal diversity was reduced, endemism enhanced and biostratigraphic resolution decreased. Indeed, the introduction of *Neogloboquadrina pachyderma* to (sub)antarctic region(s) at ~9 Ma was the last major, innovative event in planktonic foraminiferal biostratigraphy and the circumantarctic region has been dominated by virtually monospecific faunas of this taxon since then (with minor contributions from *Globigerina bulloides* and several small sized taxa). The chronology of austral/(sub)antarctic planktonic foraminiferal datum events/zones is shown in Figure 16.

Planktonic Foraminiferal Magnetobiochronology Paleogene Period.—

Paleocene Epoch.—Over 30 datum events (Table 8) have been recognized in the Paleocene Epoch including two (LAD of *M. velascoensis* and FAD of *Gl. australiformis*) which serve to denote the approximate position of the Paleocene/Eocene boundary at low and high austral latitudes, respectively. These two datum events are, however, not correlative; the FAD of *Globanomalina australiformis* has been linked in high southern latitude stratigraphies directly with the major $\delta^{13}\text{C}$ spike that

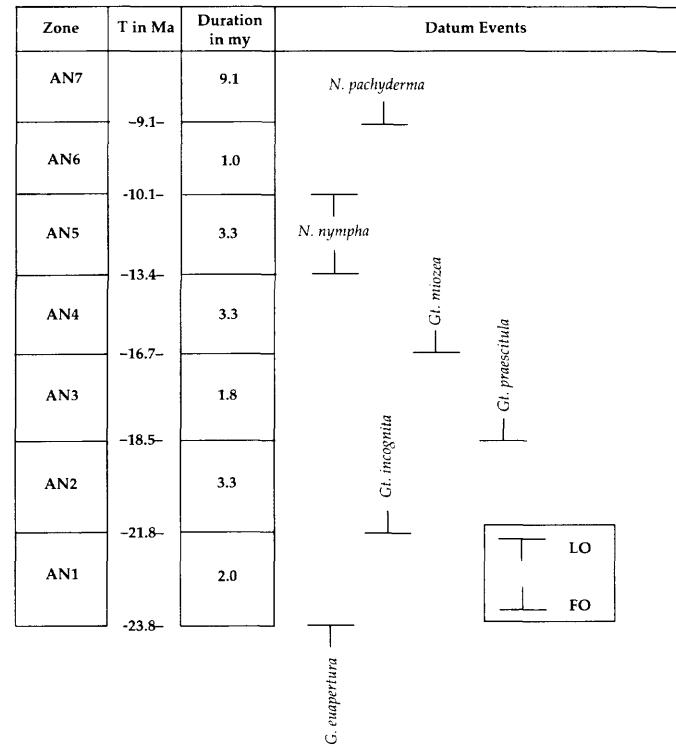


FIG. 16.—Chronology of subantarctic Neogene planktonic foraminiferal zones.

occurs in mid Zone NP9 and in early Chron C24r (Stott and Kennett, 1990), whereas the LAD of *Morozovella acuta* and *M. velascoensis* have been shown to occur within Zone NP10 and the mid part of Chron C24r (Table 8). In most instances where direct magnetobiostratigraphic correlation of a datum event has not been achieved, the relative position within a zone in which other elements are directly calibrated by magnetobiostratigraphy can be determined so that a reasonable estimate of position in a magnetic polarity chron and a corresponding age estimate can be made. The revised magnetostratigraphy used here (based on CK92/95) has the effect, essentially, of shifting the estimated ages of Paleocene datum levels in BKF85 to younger ages by ~1.5–2.7 my.

Eocene Epoch.—Nearly 40 datum levels (excluding the two which serve to delineate the approximate position of the Paleocene/Eocene boundary) have been recognized in the Eocene Epoch (Table 9), many of which serve to denote the 12 zonal (and 2 subzonal) boundaries of this epoch. Of particular interest is a series of new and revised calibrations of early Eocene datums afforded by a virtually complete stratigraphic sequence from Chron C23n to mid-Chron C24r in NE Atlantic DSDP Hole 550 (Berggren and Aubry, 1995). One problem associated with magnetobiostratigraphic calibrations across the Paleocene/Eocene boundary interval is the presence of hiatuses of brief duration which tend to concatenate datum levels; the problem is discussed elsewhere in more detail (Aubry and others, 1995; Berggren and Aubry, 1995).

Middle Eocene datum levels remain essentially those delineated in BKF85, the lack of new information attesting to the difficulty of obtaining good magnetobiostratigraphic records in the (predominantly) low latitude chert bedeviled sections, although some useful datums have been delineated at high austral latitudes for acarininid extinctions and that of *Subbotina linaperta*.

A relatively high-resolution, although not completely unequivocal, succession of datum events has been delineated for the late Eocene Epoch based on systematic, integrated studies in the Apennines and tabulated originally by Berggren and others (1992; see also Table 9). It should be noted that the LAD of *Turborotalia cerroazulensis* sensu lato is used in preference to that of *Hantkenina* spp. to denote the P17/P18 zonal boundary (Berggren and Miller, 1988) owing to the greater preservational potential of the former. Whether there is a real sequential extinction of these two taxa remains a moot point; recent studies by Leckie and others (1993) suggest that they disappear simultaneously.

The revised magnetostratigraphy of CK92/95 (and that adopted in this paper) has the effect of shifting Eocene datum levels to younger ages by ~2.5–3 my from those suggested in BKF85. The relative age spacing is similar; only the numerical values have been altered.

Oligocene Epoch.—Eighteen datum levels have been identified in the Oligocene Epoch (Table 10), their relative scarcity reflecting the significant paleoceanographic/paleoclimatic changes which occurred during this epoch. Most of the datum levels have been recognized previously (BKF85), but the calibrations are refined and/or modified here owing to new data available since 1985. However, several significant datum levels have been identified in high austral latitudes which enables relatively precise interhemispherical correlation between the

“standard” low (Berggren and Miller, 1988) and high austral (Stott and Kennett, 1990) latitude biostratigraphies.

The magnetostratigraphy of CK92/95 has the effect of shifting the Oligocene datum levels recognized in BKF85 from ~3 my (early Oligocene) to 1.5 my (mid-early late Oligocene) younger; at the Oligocene/Miocene boundary, values are essentially the same because a comparable value was used to anchor the time scale at the older end of Subchron C6C.2n (CK92/95).

Neogene Period.—

Miocene Epoch.—About 70 planktonic foraminiferal datum levels have been identified in the Miocene Epoch (Tables 11 to 13), many of which were already recognized in BKV85. We have (re)calibrated these datum levels to the revised magnetostratigraphy of CK92/95 and added several more, generally from high austral latitudes. In some instances, revisions/reinterpretations of magnetobiostratigraphy has resulted in revised age estimates for several datum levels as well. In general, we have found our current analysis and/or evaluation of new (post 1985) data to be quite consistent with earlier interpretations and/or calibrations. The major difference between this work and BKV85 is the firmer documentation of the regional correlation of the biogeographically overlapping zonal schemes adopted here within a more precise magnetostratigraphic framework. The relatively high degree of stratigraphic/chronologic resolution achievable in (sub)tropical and transitional regions should be contrasted with the significantly lower resolution in high-latitude (sub)polar latitudes. This latter fact reflects the increased, and accelerated, late Neogene cooling at high latitudes with concomitant replacement of calcareous microfaunas and floras by biosiliceous (diatom, radiolarians) components.

We have recognized some 22 datum events spanning the 7.4-my interval of the early Miocene (23.8–16.4 Ma; Table 11), or an average of about 2.9 events /1 my. Zones M1 (2.24 my), M2 (2.75 my) and M3 (1.50 my) can be contrasted with the much shorter Zones M4 and M5 (and indeed middle Miocene Zones M6, M8–10 as well), reflecting the late early to early middle Miocene global warming trend and concomitant flurry of speciation events in (sub)tropical environments. This allows fine-scaled biostratigraphic subdivision of the upper lower and middle Miocene Series. Of some consternation is the lack of a direct magnetobiostratigraphic correlation of the FAD of *Globigerinatella insueta* (which defines the base of Zone M3).

Some 25 datum events/levels have been identified in the middle Miocene Series (16.4–11.2 Ma; Table 12) interval of ~5 my or an average of 4.8 events/1 my which provides the highest degree of biostratigraphic resolution for the Cenozoic Era, except for the Pliocene Epoch where nearly 45 different types of biostratigraphic events spread over the ~3-my extent of the Pliocene Epoch provides some 15 datum events/1 my (Berggren and others, 1995). The early middle Miocene warming trend followed by a middle Miocene cooling trend was probably responsible for the high degree of middle Miocene biostratigraphic resolution. This may be contrasted and compared with the accelerated (and punctuated) cooling trends of the Pliocene Epoch responsible for the relatively high number of LADs of numerous (predominantly Miocene) taxa, the various biogeographic immigration/disappearance events, and FADs of several taxa.

TABLE 10.—OLIGOCENE PLANKTONIC FORAMINIFERAL MAGNETOBIOCHRONOLOGY.
OLIGOCENE

Datum	FO	LO	Paleomagnetic Chron	Age in Ma	Reference	Remarks
1. <i>Globorotalia kugleri</i>	X		C6Cn.2n	23.8	1	=Oligocene/Miocene boundary; Holes 516F, 558, 563 (ref. 1)
2. <i>Globigerina euapertura</i>		X	C6Cn.2n	23.8	2	Recorded near top C6Cn in Hole 748B and near base C6Cn in Holes 747A AND 747B (ref. 2)
3. <i>Globorotalia mendacis</i>	X		C6Cn.2n	23.8	1	Hole 516F (ref. 1)
4. <i>Tenuitella gemma</i>		X	C6Cr	24.3	5	Hole 747A (ref. 5)
5. <i>Globigerinoides primordius</i> (common occurrence)	X		C6Cr	24.3	1	Hole 516F (ref. 1)
6. <i>Globorotalia pseudokugleri</i>	X		C8n	25.9	3	Recorded in C8n in Hole 803D (ref. 3) AND in C7n in Hole 628A (ref. 3)
7. <i>Globigerinoides primordius</i>	X		C8r	26.7	3	Hole 628A (ref. 3); recorded in C7n (ref. 1).
8. <i>Paragloborotalia opima</i>		X	C9n _{yy}	27.1	1	=P21/P22 boundary in Berggren AND Miller (1988). Recorded between C9n AND C8n in Hole 516F (ref. 1); individuals become significantly smaller above C9n AND are not typical of <i>P. opima</i> sensu stricto in Hole 558 (ref. 1; see also discussion in Berggren AND Miller, 1988, p. 377).
9. <i>Globigerina labiacrassata</i>		X	C9n _{yy}	27.1	2, 4	=AP15/AP16 boundary in Berggren (1992); recorded at top C9n in Holes 747A and 748B (ref. 2), 689B and 690B (ref. 4) and in C8n _{yy} in Hole 747A (ref. 5).
10. <i>Globigerinita boweni</i>	X		C10n (mid)	28.5	5	Hole 747A (ref. 5)
11. <i>Chiloguembelina cubensis</i> (common occurrence)		X	C10n (mid)	28.5	1,2,5	=P21a/b boundary in Berggren and Miller (1988). Recorded in mid-part of C10n in Holes 747A (ref. 1, 5), 749 (ref. 2) and in mid-part of concatenated C9n AND C10n in Hole 748B (ref. 2) and associated approximately with C10n in Holes 689B and 690B (ref. 4). Whether this datum refers to extinction or strong reduction in numbers remains a moot point; records of discontinuous presence in reduced numbers of this taxon into basal Miocene levels continue (ref. 3).
12. <i>Globigerina angulisuturalis</i>	X		C11n _{yy}	29.4	1,3	Berggren and Miller (1988); Holes 516 and 558 (ref. 1), 628A and 803C (ref. 3).
13. <i>Tenuitellinata juvenilis</i>	X		(C11n)	(29.7)	5	Interval of no polarity data between normal polarity intervals interpreted as parts of C11 in Hole 747A (ref. 5).
14. <i>Subbotina angiporoidea</i>		X	C11n _{yy}	30.0	1,2,4	=P19/P20 boundary in Berggren and Miller (1988) and AP13/AP14a zonal boundary in Stott and Kennett (1990). Recorded in early part of C11n in Holes 516F (ref. 1), 748B (ref. 2), and 689B and 690B (ref. 4).
15. "Turborotalia" <i>ampliapertura</i>	X		C11r	30.3	1,6	Recorded in C11r in Holes 516F and 558 (ref. 1) and St. Stephen's Quarry, Alabama borehole (ref. 4).
16. <i>Paragloborotalia opima</i> <i>opima</i>	X		C12n (mid)	30.6	1	Hole 558 and elsewhere (ref. 1).
17. <i>Pseudohastigerina</i> spp.		X	C11r	32.0	1,6	Holes 516F, 558, 563 (ref. 1) and St. Stephen's Quarry, Alabama borehole (ref. 6).
18. <i>Cassigerinella chipolensis</i>	X		C13r	33.65	6	St. Stephen's Quarry, Alabama borehole (ref. 6).

¹Berggren and others, 1985b²Berggren, 1992³Leckie and others, 1993⁴Stott and Kennett, 1990⁵Li and others, 1992⁶Miller and others, 1993

Some 23 datum events have been recognized in the 5.9-my interval of the late Miocene (11.2–5.3 Ma; Table 13), or an average of ~3.9 events/1 my. Of particular significance is the replacement of the *Gt. merotumida-plesiotumida* group by *Gt. lengaensis* in subdividing the upper Miocene Series (see discussion above) of (sub)tropical and transitional regions which provides more confident calibration to the GPTS. The joint occurrence of the FAD of *Gt. sphericomicoza* and *Gt. tumida* at DSDP Hole 519 has provided a means of regional correlation between (sub)tropical and transitional regions at the Miocene/Pliocene boundary (5.2 Ma in the chronology of CK92; 5.3 Ma in CK92/95 and herein; see discussion below under Chronostratigraphy).

Pliocene-Pleistocene Epochs.—A comprehensive compilation has recently been made of some 45 Pliocene and 10 Pleistocene planktonic foraminiferal datum events in connection with a larger review of the current status of late Neogene (Pliocene-Pleistocene) astro-and magnetobiochronology (Berggren and

others, 1995) and the interested reader is referred to that source for additional information.

Calcareous Nannofossil Magnetobiochronology Paleogene Period.—

Progress in Paleogene calcareous nannofossil magnetochronology has been uneven since the publication of Berggren and others (1985b). No synthesis of post 1985 magnetobiostratigraphic correlation has been published for the Cenozoic. This includes the magnetobiochronology of Wei and Peleo-Alampay (1993) which is mostly a conversion of the biochronology in Berggren and others (1985b) to the (obsolete) magnetochronology of Cande and Kent (1992). Little attention has been paid to Paleocene biochronology, except for the Southern Ocean (Wei, 1992), whereas efforts have been concentrated on late middle Eocene to Oligocene biochronology (Premoli Silva and others, 1988a; Wei, 1991; Wei and Wise, 1992). The compila-

TABLE 11.—EARLY MIocene PLANKTONIC FORAMINIFERAL MAGNETOBIOCHRONOLOGY.
EARLY MIocene

Datum	FAD	LAD	Paleomagnetic Chron	Age in Ma	Reference	Remarks
1. <i>Praeorbulina sicana</i>	X		C5Cn.2n (mid)	16.4	1	=M4b/c boundary.
2. <i>Globorotalia incognita</i>		X	C5Cn.2n (mid)	16.4	2	
3. <i>Globorotalia miozea</i>	X		C5Cn.3n _(o)	16.7	2	Hole 751, Kerguelen Plateau.
4. <i>Globorotalia birnageae</i>	X		C5Cn.3n _(o)	16.7	1	=M4a/b boundary; Hole 516, South Atlantic (ref. 1).
5. <i>Globorotalia zealandica</i>		X	C5Dn _(y)	17.3	3	Hole 747A, (ref. 3); observed in C5Dn _(o) in Hole 751 (ref. 2).
6. <i>Globorotalia semivera</i>		X	C5Dn _(y)	17.3	1	
7. <i>Catapsydrax dissimilis</i>		X	C5Dn _(y)	17.3	1	=M3/M4 boundary; Holes 558, 563 North Atlantic (ref. 1); observed at top of C5Dr in Hole 608 in interval of strong dissolution (refs. 2, 3).
8. <i>Globoquadrina dehiscens forma spinosa</i>		X	C5Dr	17.9	1	Hole 516, South Atlantic (ref. 1).
9. <i>Globorotalia praescitula</i>	X		C5En	18.5	2,4	Holes 747A, 748B, 751 (ref. 2), and 608 (ref. 4); recorded in earliest part of C5En in Hole 516F (ref. 1).
10. <i>Globigerinatella insueta</i>	X		(C5En)	(18.8)		=M2/M3 boundary; polarity chron and age estimate inferred here (see text for discussion).
11. <i>Globigerinoides altiaperturus</i>	X		C6An _(y)	20.5	1,5	Hole 516F, South Atlantic (ref. 1); recorded in older part of C6r in Contessa Highway Section (ref. 5).
12. <i>Tenuitella munda</i>		X	C6Ar	21.4	3	Hole 747A, Kerguelen Plateau (ref. 3); magnetostratigraphy reinterpreted in ref. 6.
13. <i>Globorotalia kugleri</i>		X	C6Ar	21.5	1,5	=M1/M2 boundary; Hole 516 F, South Atlantic (ref. 1) and at base C6An in Contessa Highway Section (ref. 5).
14. <i>Globorotalia incognita</i>	X		C6Ar	21.6	2	Hole 747A (ref. 2); magnetostratigraphy reinterpreted in ref. 6.
15. <i>Globoturborotalita angulisuturalis</i>		X	C6Ar	21.6	1	Hole 516F (ref. 1); magnetic stratigraphy reinterpreted in ref. 6.
16. <i>Globorotalia pseudokugleri</i>		X	C6Ar	21.6	1	Hole 516F (ref. 1); magnetic stratigraphy reinterpreted in ref. 6.
17. <i>Globoquadrina dehiscens forma spinosa</i>	X		C6Aar.1n	22.2	1	Hole 515F (ref. 1).
18. <i>Globoquadrina globularis</i>		X	C6Bn.1r	22.8	1	Hole 516F, South Atlantic (ref. 1).
19. <i>Globoquadrina dehiscens</i>	X	X	C6Br	23.2	1	=M1a/b boundary; Holes 516F, 558, 563 (ref. 1); South Atlantic (refs. 7, 8) and Contessa Highway Section.
20. <i>Globigerina euapertura</i>		X	C6Cn.2n	23.8	2	Holes 747A, 747B (ref. 2); reported in C6Cn.1n in Hole 747A in ref. 3.
21. <i>Globorotalia kugleri</i>	X		C6Cn.2n	23.8	1	=P22/M1 boundary; Holes 558, 563 (North Atlantic) and 516F (South Atlantic) (ref. 1).

¹Berggren and others, 1985a²Berggren, 1992³Li and others, 1992⁴Miller and others, 1994⁵Montanari and others, 1991⁶Wright and Miller, 1992⁷Poore and others, 1983⁸Poore and others, 1984

tion given below (Tables 14–17) shows dramatically that the number of sections with a reliable magnetostratigraphy is extremely small, and that there are intervals such as the middle Eocene Series (Zones NP14 to NP16 in particular) where biostratigraphic events are still poorly tied to magnetochronology. It is clear that the advances in magnetobiochronology around the Eocene/Oligocene boundary (Premoli Silva and others, 1988a; Berggren and others, 1992) and more recently around the Paleocene/Eocene boundary (Aubry and others, 1995; Berggren and Aubry, 1995) have been fostered by the activities of Working Groups (in these cases IGCP Projects 174 (Terminal Eocene Events) and 308 (Paleocene/Eocene Boundary Events in Time and Space)). We expect that with the recent creation of Working Groups on Paleogene stages, additional improvements to magnetobiostratigraphic correlations in the least well documented stratigraphic intervals will be made in the next few years.

The major question when establishing a magnetobiochronologic framework concerns the temporal reliability of the paleontologic events. The view that many FADs and LADs of Cenozoic calcareous nannofossil species are unreliable owing to preservational problems or to latitudinal diachrony has been amply discussed (Backman, 1987; Dowsett, 1988; Miller and others, 1994; Monechi and Thierstein, 1985; Spencer-Cervato and others, 1994; Wei 1991, 1992; Wei and Wise, 1989, 1990). This view is based on the assumption that discrepancies in mag-

netobiostratigraphic correlations between sections reflect diachrony. We suggest instead that undeciphered unconformities in the stratigraphic record (and to a lesser extent differences in taxonomic concepts) are more likely to account for such discrepancies (see Aubry, this volume; Aubry and others, 1995), although we recognize that diachrony occurs (Aubry, 1992a, b). It is beyond the scope of this paper to discuss in detail the reliability of every Cenozoic calcareous nannofossil datum. Comments are made in Tables 14 to 17 to this effect. They reveal that claims of diachrony of small amplitude (<2 my) are poorly substantiated, at least in the Paleocene and Eocene Epochs (Tables 14, 15). Two examples taken from the Paleocene Epoch—the FAD of *Ellipsolithus macellus* and the FAD of *Heliolithus kleinpellii*—are however discussed in detail below to illustrate that stratigraphic sections must be submitted to a comprehensive examination before magnetobiostratigraphic correlations are established.

The lowest occurrence (LO) of *Ellipsolithus macellus* defines the NP3/NP4 and the CP2/CP4 zonal boundaries in the zonal schemes of Martini (1971) and Bukry (1973), respectively. This datum is generally regarded as temporally unreliable owing to the assumed susceptibility of the coccolith towards dissolution or to environmental restriction of the species (e.g., Monechi and Thierstein, 1985; Wei and Wise, 1989). Monechi and Thierstein (1985) observed that in the Contessa and the Bottaccione sections, Italy, the LO of *E. macellus* is in Chron C28r whereas in

TABLE 12.—MIDDLE MIocene PLANKTONIC FORAMINIFERAL MAGNETOBIOCHRONOLOGY.
MIDDLE MIocene

Datum	FAD	LAD	Paleomagnetic Chron	Age in Ma	Reference	Remarks
1. <i>Neogloboquadrina mayeri</i>		X	C5r.2r	11.4	1-4	See discussion in text on Late Miocene and refs. 1-4.
2. <i>Globoturborotalita nepenthes</i>	X		C5r.3r	11.8	1-4	M10/M11 boundary; occurs in North Atlantic Sites 563 (ref. 1) and 608 (ref. 3) and basal Buff Bay Formation, Jamaica (refs. 2, 4).
3. <i>Globorotalia panda</i>		X	C5r.3r	11.8	2	Hole 747A (Kerguelen Plateau, S. Indian Area); magnetic stratigraphy reinterpreted in ref. 5.
4. <i>Globorotalia praescitula</i>		X	C5An.1n	11.9	6	Hole 747A; see remarks in item 3 above.
5. <i>Globorotalia foehsi robusta</i>	X		C5An.1n	11.9	1	M9/M10 boundary; Hole 563 (ref. 1).
6. <i>Globorotalia foehsi lobata</i>		X	C5An.1r	12.1	1,5	= M9a/b boundary; based on reinterpretation of paleomagnetics in Hole 563, based in turn on stable isotope studies at Kerguelen Plateau Site 747 and North Atlantic Hole 608 (ref. 5).
7. <i>Globorotalia foehsi robusta</i>	X		C5An.2n	12.3	1,6	See revised interpretation of magnetostratigraphy of 563 based on stable isotope studies in ref. 5.
8. <i>Tenuitella clemenciae</i>		X	C4An.2N	12.3	7	Hole 747A.
9. <i>Tenuitella minutissima</i>		X	C5An.2n	12.3	7	Hole 747A.
10. <i>Tenuitella pseudoedita</i>	X		C5An.2n	12.3	7	Hole 747A.
11. <i>Tenuitella selleyi</i>		X	C5An.2n	12.3	7	Hole 747A.
12. <i>Globorotalia foehsi lobata</i>	X		C5Ar.1r	12.5		= M8/M9 boundary; revised interpretation of magnetostratigraphy of Hole 563 (ref. 5) indicates FAD of <i>Gr. foehsi lobata</i> in C5Ar.1r (ref. 5) rather than C5Ar (ref. 1).
13. <i>Globorotalia foehsi</i> s.str.	X		C5Ar.1n-2n (undiff.)	12.7	1,5	= M7/M8 boundary; reinterpretation of magnetostratigraphy at Hole 563 based on stable isotope studies at 747A and 608 (see ref. 5).
14. <i>Globorotalia praefohsi</i>	X		C5Ar.1n-2n (undiff.)	12.7	1,5	See remarks, item 13 above.
15. <i>Neogloboquadrina nympha</i>	X		C5ABn	13.4	5,6	Holes 747A, 751, Kerguelen Plateau (ref. 6). In Hole 608 occurs in sample assigned to C5AAr, just above C5ABn (ref. 5).
16. <i>Globorotalia peripheroronta</i>		X	C5ADn _(o)	14.6	1	
17. <i>Globorotalia peripheroacuta</i>	X		C5Bn.1n	14.8	1	= M6/M7 boundary.
18. <i>Praeorbulina sicana</i>		X	C5Bn.1n	14.8	1	
19. <i>Praeorbulina glomerosa</i> s. str.		X	C5Bn.1n	14.8	1	
20. <i>Orbulina suturalis</i>	X		C5Bn.2n	15.1	1	= N5/N6 boundary.
21. <i>Globorotalia miozea</i>		X	C5Br _(o)	15.9	6	Hole 747A; recorded in C5B.1n in ref. 7.
22. <i>Praeorbulina circularis</i>	X		C5Cn.1n _(o)	16.0	1	
23. <i>Praeorbulina glomerosa</i> s.str.	X		C5Cn.1n _(o)	16.10	1	= M4/M5 boundary.
24. <i>Globigerinoides diminutus</i>	X		(C5Cn.2n)	(16.1)	1	See remarks in ref. 1.
25. <i>Praeorbulina curva</i>	X		C5Cn (undiff., mid part)	16.3	1	
26. <i>Praeorbulina sicana</i>	X		C5Cn.2n (mid)	16.4	1	= Subzone M4b/c boundary.
27. <i>Globorotalia incognita</i>		X	C5Cn.2n (mid)	16.4	6	Hole 747C, Kerguelen Plateau.

¹Berggren and others, 1985a

²Berggren, 1993

³Miller and others, 1991

⁴Miller and others, 1994

⁵Wright and Miller, 1992

⁶Berggren, 1992

⁷Li and others, 1992

DSDP Holes 577 and 577A on the Shatsky Rise (NW equatorial Pacific), and in DSDP Hole 527 on the Walvis Ridge (South Atlantic), it lies in Chron C26r. Subsequently, Wei and Wise (1989) determined that *E. macellus* occurred 1 my earlier at DSDP Site 516 in the western South Atlantic (Rio Grande Rise) than at eastern South Atlantic sites (Walvis Ridge) as determined by Shackleton and others (1984). Referring to Monechi and Thierstein (1985), they remarked on the unreliability of the datum.

The age derived by Shackleton and others (1984) for the FAD of *E. macellus* was based in particular on DSDP Site 527 where Manivit (1984) recorded the LO of the species between samples 527-30-2, 150 cm [?50 cm] and 527-30-2, 70 cm, that is, slightly above the magnetic polarity reversal interpreted as the Chron C26r/C27n boundary in the hole (Chave, 1984; Shackleton and others, 1984). Our work (MPA) shows that the LO of *E. macellus* in Hole 527 lies between Core 31-1, 59-61 cm and 31-2, 82-83 cm, that is, in an interval of undetermined polarity

well below (~8 m) the Chron C26r/C27n boundary and slightly above (~1 m) Chron C28n (the Chron C27r/C28n boundary is not located in Hole 527). As all other Paleocene species, *E. macellus* shows a rapid increase in size in its lower range. Its earliest morphotypes are small and the central area of the coccolith may be more prone to dissolution than in later morphotypes. For these reasons, they are easily overlooked although well characterized by the extinction pattern typical of the taxon. In both Holes 527 and 516F, the LO of *E. macellus* is in Chron C27r. The precise position of this event with respect to the Chron C27r/C28n boundary cannot be determined however because of poor recovery in Hole 516F and because the chron boundary is not located in Hole 527.

The apparent location of the LO of *E. macellus* in Chron C26r in Hole 528 by Shackleton and others (1984) results from a misinterpretation of the interval with normal polarity in Core 30, sections 3 and 4, possibly based on the belief of the stratigraphic relation between Chron C27n and the LO of *E. macel-*

TABLE 13.—LATE MIocene PLANKTONIC FORAMINIFERAL MAGNETOBIOCHRONOLOGY.
LATE MIocene

Datum	FAD	LAD	Paleomagnetic Chron	Age in Ma	Reference	Remarks
1. <i>Globorotalia sphericomiozea</i>	X		C3r	5.6	1	Hole 588 (SW Pacific).
2. <i>Globorotalia pliozea</i>	X		C3r	5.6	1	Hole 588.
3. <i>Globorotalia tumida</i>	X		C3r	5.6	1-4	M14/PL1 boundary; Hole 588; synchronous in the SW Pacific (586B, 587, 588, 590) and Indian (114, 219, 237, 238) Oceans (ref. 3). Identified at comparable position without paleomagnetic control at ODP Hole 806B (Ontong-Java Plateau equatorial Pacific; ref. 4).
4. <i>Globoquadrina dehiscens</i>	X		C3r	5.8	1-4	See remarks under 3 above.
5. <i>Globorotalia lenguaensis</i>	X		C3An.1n	6.0	4	M13/M14 boundary. Directly calibrated to C3An.1n in ODP Hole 840 (Tonga Platform; ref. 4) and directly to this level in Hole 806B (Ontong-Java Plateau equatorial west Pacific; ref. 5); LAD occurs just below FAD of <i>P. primalis</i> at ODP 840 and just above it at ODP 806B (see below). In Hole 519 (South Atlantic LAD of <i>Gt. lenguaensis</i> has been calibrated to C4An _{1y} (~8.7 Ma; CK 95) (Poore and others, 1983, 1984). =M13/M14 boundary; Hole 519, South Atlantic. The LAD of <i>G. lenguaensis</i> in E68–136 (Gulf of Mexico) occurs about 35' above the FAD of <i>G. plesiotumida</i> (=N16/N17) and within the range of <i>Minilitha convallis</i> and above the LAD of <i>Discoaster bollii</i> . In E66–73 (Gulf of Mexico) the LAD of <i>G. lenguaensis</i> occurs at same level as FAD of <i>G. plesiotumida</i> (=N16/N17) and below the FAD of <i>M. convallis</i> and the LAD of <i>D. bollii</i> (Zhang and others, 1993; Aubry, 1993b).
6. <i>Globorotalia margaritae</i>	X		C3An (mid)	6.0	1-7	North Atlantic; refs. 2, 6, 7; late Miocene at Site 588 (ref. 1) and considered asynchronous between SW Pacific and Indian Ocean (ref. 3); recorded above FAD <i>G. tumida</i> in Hole 806B (equatorial Pacific) (ref. 4). FAD calibrated to C3An.2n in ODP Hole 840 (Tonga Platform; ref. 4, below FAD of <i>G. tumida</i> . Initial occurrence in Mediterranean recorded immediately above base Zanclean in mid-Thvera at 4.93 Ma (Langereis and Higen (1991) and First Common Occurrence (FCO) only shortly thereafter at 4.89 Ma (Langereis and Hilgen 1991; ref. 7).
7. <i>Pulleniatina primalis</i>	X		C3An.2n	6.4	2-3,5	LAD simultaneous in SW Pacific (DSDP Sites 587, 588, 590) and Indian Ocean (DSDP Sites 214, 219, 238; ref. 3). Also recorded at comparable level in ODP Hole 806B (ref. 4) without paleomagnetic calibration. Recorded slightly above FAD <i>G. lenguaensis</i> at ODP Hole 840 (ref. 4).
8. <i>Neogloboquadrina acostaensis</i> (S to D)	X		C3An.2n	6.2	3	
9. Dextral menardine globorotaliids (= <i>Globorotalia menardii</i> form 5)	X		C3An.2r	6.4	3	
10. <i>Neogloboquadrina acostaensis</i> (D to S)	X		C3An.2r	6.6	3	
11. <i>Neogloboquadrina atlantica</i> (D to S)	X		C3Ar	6.8	7,8	North Atlantic DSDP Hole 609, 611 (age inferred; ref. 7); 642 (paleomag calibration, ref. 8).
12. <i>Globorotalia conomicoza</i>	X		C3Br.1r	7.12	9	=Mt 8/Mt9 boundary = Tortonian/Messinian boundary; Cretan sections (ref. 8); recorded in mid-C3An in Mediterranean in ref. 7; see also ref. 1, 2. Paleomagnetic age estimated (this paper) agrees closely with an estimated age of 7.26 ± 5.1 Ma for Tortonian/Messinian boundary in NE Apennines based on ⁴⁰ Ar/ ³⁹ Ar age of 7.33 Ma just below FAD of <i>Gt. conomicoza</i> (Vai and others, 1993).
13. <i>Globorotalia menardii</i> form 5	X		C3Br.2r	7.2	9	Cretan sections (ref. 9).
14. Sinistral menardine globorotaliids (<i>G. menardii</i> form 4)	X		C3Br.3r	7.4	9	Cretan sections (ref. 9); see discussion in refs. 2, 9, 10.
15. <i>Globorotalia suterae</i>	X		C4n.2n	7.8	10	Hole 654, Mediterranean. Paleomagnetic age estimate (this paper) agrees perfectly with ⁴⁰ Ar/ ³⁹ Ar age of 7.72 ± 0.15 Ma on this datum in the northern Apennines (Vai and others, 1993).
16. <i>Globorotalia cibaoensis</i>	X		(C4n.2n)	(7.8)	5	ODP Hole 806B (Ontong-Java Plateau). Age estimate in ref. 5, Table 3 of 6.7 Ma calibrated to BKVC85 is incorrect. Note that FAD of <i>Gt. cibaoensis</i> is at virtually same level as FAD <i>Gt. plesiotumida</i> (~266-m) but that this level is incorrectly estimated (296.75-m) in Table 2 and plotted Figure 6. The FADs of <i>Gt. cibaoensis</i> (6.7 Ma), <i>Gt. juanai</i> (6.8 Ma), <i>Candeina nitida</i> (6.8 Ma) and <i>Globigerinoides extremus</i> (6.9 Ma) are all shown to be younger than that of <i>Gt. plesiotumida</i> (7.1 Ma = BKVC 85) although their FADs range from ~3 to 23-m below the FAD of <i>Gt. plesiotumida</i> . The incorrect ages were derived by misplotting the FAD of <i>Gt. plesiotumida</i> (7.1 Ma) at 297-m on Figure 6 and then calculating ages of the other datums by interpolating upward to their correct depths. Correct age estimates have been made here based on the stratigraphic position of these datums in Hole 806B.

TABLE 13.—Continued.
LATE MIocene

Datum	FAD	LAD	Paleomagnetic Chron	Age in Ma	Reference	Remarks
16. <i>Globorotalia juanai</i>	X		(C4r.1r)	(8.1)	5	ODP Hole 806B; see remarks under 14 above.
17. <i>Candeina nitida</i>	X		(C4r.1r)	(8.1)	5	ODP Hole 806 B; see remarks under 14 above.
18. <i>Globigerinoides extremus</i>	X		(C4r.2r)	(8.3)	5	ODP Hole 806 B; See remarks above.
19. <i>Globorotalia plesiotumida</i>	X		(C4r.2r)	(8.3)	5	ODP Hole 806B. The FAD of this form is shown to occur in Core 29H (with the FAD of <i>G. cibaoensis</i>) in Zone NN11, but questionable occurrences are recorded as low as Core 31H at the same level as the FAD of <i>Gl. extremus</i> (in low NN10). FAD recorded in upper part of Zone NN10, overlapping upper part of range of <i>Discoaster bollii</i> for almost 3 m and ~4 m below FAD of <i>Minylitha convallis</i> at E68–136 (Gulf of Mexico) (Zhang and others, 1993; Aubry, 1993b). FAD occurs ~20 m below <i>M. convallis</i> in E66–73 (Zhang and others, 1993; Aubry, 1993b). At Buff Bay, Jamaica, the type level of <i>G. plesiotumida</i> (Blow, 1969, 1979) is in Zone NN10 (Berggren, 1993; Aubry, 1993a)
20. <i>Neogloboquadrina humerosa</i>	X		C4r.2r	8.5	2	
21. <i>Neogloboquadrina pachyderma</i>	X		C4Ar.1n	>9.2	11	Holes 748, 751 (Kerguelen Plateau, South Indian Ocean).
22. <i>Neogloboquadrina nymphe</i>		X	C5n.2n	10.1	11	Holes 748, 751 (Kerguelen Plateau, South Indian Ocean).
23. <i>Neogloboquadrina acostaensis</i>	X		C5n.2n	10.9	2,12	Holes 558 and 563 (ref. 2) and 608 (ref. 12) in North Atlantic.
24. <i>Neogloboquadrina mayeri</i>		X	C5r.2r	11.4	2,12,13	M12/M13 boundary; lower part of Buff Bay Formation at Buff Bay, Jamaica, 3 m above FAD of <i>Discoaster hamatus</i> (Berggren, 1993; Aubry, 1993a). In Bodjonegoro 1 borehole (Indonesia) these two datum levels occur together (pers. observ., WAB, MPA). In North Atlantic Sites 558, 563 (ref. 2) and 608 (ref. 12) LAD of <i>N. mayeri</i> was observed in close juxtaposition with FAD of <i>N. acostaensis</i> , essentially eliminating Zone N15 (=M12). This has been variously interpreted as due to a hiatus in the North Atlantic (Aubry, 1993a) or diachrony (ref. 12, 13).

¹Hodell and Kennett, 1986²Berggren and others, 1985a³Srinivasan and Sinha, 1992⁴Chaproniere and others, 1994⁵Chaisson and Leckie, 1993⁶Weaver and Clement, 1986⁷Weaver and Clement, 1987⁸Spiegler and Jansen, 1989⁹Krijgsman and others, 1994¹⁰Glacon and others, 1990¹¹Berggren, 1992¹²Miller and others, 1991¹³Miller and others, 1994

lus in Hole 527. Planktonic foraminiferal stratigraphy which indicates that Core 30–2 belongs to Zone P1b (Boersma, 1984) supports our revised identification of the normal polarity interval in Core 30 as Chron C28n rather than C27n.

Monechi and Thierstein (1985) recorded the lowest occurrence of *E. macellus* in Chron C27r in both the Bottaccione and Contessa Highway sections (Monechi and Thierstein, 1985, Figs. 2, 6), not in Chron C28r as claimed by Monechi and others (1985). The discrepancy between the Italian and the South Atlantic sections is thus considerably reduced if not annulled. Monechi and others (1985) correlated the LO of *E. macellus* with a level low in Chron C26r in Holes 577 and 577A. Although no interval with a normal polarity representing Chron C27n was recorded in Hole 577, they assumed that this chron corresponded to a gap in the sample record correlative with a normal polarity interval between 100.95 and 101.95 mbsf in Hole 577A and identified by them as Chron C27n (Monechi and others, 1985, Fig. 2). In Hole 577, the LO of *E. macellus* (at 100.20 mbsf) is slightly above the LO of *Sphenolithus primus* and just below the LO of *Fasciculithus pileatus*. In Hole 577A, it is just above the LO of *F. pileatus* and immediately below the LO of *S. primus*. In both holes, it is (~2 m) below the LO of *Fasciculithus tympaniformis* (at 98 mbsf in Hole 577; at 97.50 mbsf in Hole 577A) and in an interval with reversed polarity which Monechi and others (1985) identified as Chron C26r. Magnetobiostratigraphic correlations in other Paleocene sections (Sites 384, 527, 772C, Bottaccione) support their chron identification.

However, in these sections, the LOs of *S. primus*, *F. pileatus* and *F. tympaniformis* lie in mid Chron C26r, not immediately above the Chron C26r/C27n boundary. In addition, the close association of the LO of *E. macellus*, *S. primus* and *F. pileatus* indicates that only the upper part of Zone NP4 occurs in Holes 577 and 577A. Both the biostratigraphic evidence and the magnetobiostratigraphic correlations imply that the range of *E. macellus* is truncated in the two holes. An unconformity occurs at ~100.9 mbsf in Hole 577A and ~101.8 mbsf in Hole 577. The stratigraphic gap encompasses the lower part of Zone NP4 and an undetermined part of Zone NP3 and the hiatus comprises the early part of Chron C26r, Chron C27n, and most of Chron C27r (represented between 101.8 and 102.95 mbsf) in Hole 577 and all of Chron C27r in Hole 577A. We deduce from this that the normal polarity interval between 100.95 and 101.95 mbsf in Hole 577A does not represent Chron C27n but is part of Chron C28n.

We conclude that diachrony of the FAD of *E. macellus* between the Atlantic Ocean and the eastern equatorial Pacific is not demonstrated. Instead sections with a good magnetostratigraphic record show that the FAD of *E. macellus* lies in the early part of Chron C27r.

Heliolithus kleinelli is another species whose lowest occurrence has been suggested to be diachronous. Wei and Wise (1989) indicated that it occurs at various levels in Chron C26r (DSDP Sites 516, 527, 577), Chron C25n (Bottaccione and Contessa Highway sections) and Chron C25r (DSDP Hole 528)

TABLE 14.—RELATIONSHIP OF PALEOCENE CALCAREOUS NANNOFOSSIL DATUM LEVELS TO OBSERVED (AND INTERPRETED) MAGNETIC POLARITY STRATIGRAPHY, AND CALCAREOUS NANNOFOSSIL PALEOCENE CHRONOLOGY. AGE ESTIMATES (MA) DERIVED FROM THE GPTS OF CANDE AND KENT (1992/1995) AND ADOPTED IN THIS PAPER.

PALEOCENE

Datum	FAD	LAD	Paleomagnetic Chron	Age in Ma	Reference	Remarks
1. <i>Tribrachiaetus bramlettei</i>	X		Chron C24r	55	2,3	See text for discussion
2. <i>Rhomboaster cuspis</i>	X		Chron C24r	55.16	2,3	See text for discussion
3. <i>Fasciculithus tympaniformis</i>		X	Chron C24r	55.33	2,3	See text for discussion
4. <i>Cruciplacolithus eodelus</i>	X		Chron C24r	55.5	7	LO of this species precedes closely the carbon isotope excursion in many DSDP sites, in particular at Site 577 (ref. 7).
5. <i>Discoaster multiradiatus</i>	X		Chron C25n	56.2	9	Mid Chron C25n in Holes 577 (ref. 9), 752A (ref. 12) and in Contessa Highway section (ref. 8). Lower part of magnetozone assigned to Chron C25n in Hole 384 but exact location indeterminate because of poor recovery and unconformity (ref. 1). Just above magnetozone interpreted as Chron C25n in Hole 689 (ref. 15) and Hole 690 (ref. 2, but see remark on extreme scarcity of discoasters at this site).
6. <i>Discoaster okadai</i>	X		Chron C25r	56.8	1	Slightly above FAD of <i>D. nobilis</i> in Hole 384 (ref. 1); coincident with FAD of <i>D. nobilis</i> in Hole 577A and slightly below FAD of <i>D. nobilis</i> in Hole 577 (ref. 7).
7. <i>Discoaster nobilis</i>	X		Chron C25r	56.9	1	Mid part of magnetozone interpreted as Chron C25r in Hole 384 (ref. 1). Uppermost part of magnetozone interpreted as Chron C25r in the Contessa Highway section (ref. 8) and in Hole 577 (ref. 9). Basal part of magnetozone interpreted as Chron C25n in Hole 752A (ref. 12). Lowermost part of magnetozone assigned to Chron C25r in Hole 577A (ref. 9); however identification of the normal polarity interval between 88.91 and 89.81 mbsf in Hole 577A (Bleil, 1985) as Chron C26n (ref. 9) is incorrect. Similarly, identification of the normal polarity interval between 91.47 and 92.30 mbsf in Hole 577 (Bleil, 1985) as Chron C26n (ref. 9) is improper.
8. <i>Heliolithus riedelii</i>	X		Chron C25r	57.3	1	Lower part of magnetozone interpreted as Chron C25r in Hole 384 (ref. 1). Occurs in magnetozone interpreted as Chron C25r in the Thanet Beds.
9. <i>Discoaster mohleri</i>	X		Chron C25r	57.5	1	Lowermost part of magnetozone interpreted as Chron C25r in Holes 384 (ref. 1) and 762 C (cf. refs. 6 and 14); poorly constrained in magnetozone assigned to Chron C25r in Holes 527 (ref. 1) and 752A (ref. 12) because of poor recovery. But mid part of upper normal polarity interval assigned to Chron C26n (Alvarez and others, 1977; Napoleone and others, 1983) in the Bottaccione section and in upper part of middle normal polarity interval assigned to Chron C26n (Lowrie and others, 1982) in the Contessa Highway section (ref. 8).
10. <i>Hornibrookina teuriensis</i>		X	Chron C26r	58.3	11	HO recorded just above LO of <i>H. kleinelli</i> in Hole 690B (ref. 11) in an interval without magnetostratigraphy but likely below Chron C26n following Spiess's data (1990).
11. <i>Sphenolithus anarrhopus</i>	X		Chron C26r	58.4	1	Essentially coincident with the FAD of <i>H. kleinelli</i> in Holes 384 and 527 (ref. 1). Slightly below the FAD of <i>H. kleinelli</i> in Hole 577 (ref. 7). Slightly above the FAD of <i>H. kleinelli</i> in Hole 577 and coincident with the FAD of <i>D. mohleri</i> in Hole 577A (ref. 7); these relationships are interpreted here as indicative of an unconformity which implies that no magnetozone corresponding to Chron C26n was recovered in Hole 577A contrary to Bleil (1985) and ref. 9 (see text).
12. <i>Heliolithus kleinelli</i>	X		Chron C26r	58.4	1	Upper fourth of magnetozone interpreted as Chron C26r in Hole 527 (cf. refs. 1 and 13), in Hole 762C (cf. refs. 6 and 14) following reinterpretation of Galbrun's identification (ref. 6) of polarity intervals in Core 31 and in Hole 752A (ref. 12). But lower part of upper normal polarity interval assigned to Chron C26n (Alvarez and others, 1977; Napoleone and others, 1983) in the Bottaccione section and mid part of lower normal polarity interval assigned to Chron C26n (Lowrie and others, 1982) in the Contessa Highway section (ref. 8). The different correlations between magnetozones and the LO's of <i>H. kleinelli</i> and <i>D. mohleri</i> in the Italian sections compared to other sections lead to question the identification of Chron C26n in the Bottaccione and the Contessa Highway sections.
13. <i>Chiasmolithus consuetus</i>	X		Chron C26r	59.7	1	Mid part of magnetozone assigned to Chron C26r in Holes 384 and 527 (ref. 1); upper part of magnetozone assigned to Chron C26r in Hole 762C (cf. refs. 6 and 14).
14. <i>Fasciculithus tympaniformis</i>	X		Chron C26r	59.7	1	Mid part of magnetozone assigned to Chron C26r in Hole 384 (ref. 1) and in the Bottaccione section (ref. 8); lower part of magnetozone interpreted as Chron C26r in Holes 752A (ref. 12), 762C (cf. refs. 6 and 14) and in the Contessa Highway section (ref. 8).
15. <i>Fasciculithus ulii</i>	X		Chron C26r	59.9	1	Lower third of magnetozone interpreted as Chron C26r in Holes 384 (ref. 1) and 762C (cf. refs. 6 and 14). LO poorly constrained in Hole 527 because of poor recovery (ref. 1).
16. <i>Sphenolithus primus</i>	X		Chron C26r	60.6	1	1/5th above the magnetic polarity reversal interpreted as the Chron C26r/C27n boundary in Holes 527 and 384 (ref. 1).

TABLE 14.—Continued.
PALEOCENE

Datum	FAD	LAD	Paleomagnetic Chron	Age in Ma	Reference	Remarks
17. <i>Chiasmolithus bidens</i>	X		Chron C26r	60.7		Lowermost part of magnetozone interpreted as Chron C26r in Hole 384 (ref. 1). Lower part of magnetozone interpreted as Chron C26r in Hole 762C (cf. refs. 6 and 14); upper part of magnetozone interpreted as Chron C26r in Hole 577A, but lower part of magnetozone interpreted as Chron C27r in Hole 577 (cf. refs. 7 and 9; see text for discussion). Mid part of magnetotozone interpreted as chron C26r in Hole 527 (ref. 1) and (through indirect correlation) in Hole 738C (ref. 16).
18. <i>Ellipsolithus macellus</i>	X		Chron C27r	62.2	1	Associated with lower half of magnetozone assigned to Chron C27r in Hole 384 (ref. 1); with the lower part of an interval of unknown polarity between Chron C27n and C28n in Hole 527 (ref. 1); with an interval of unknown polarity immediately above the magnetozone interpreted as Chron C28n in Hole 516F (cf. refs. 2 and 17); with mid part of magnetozone interpreted as Chron C27r in the Contessa Highway section (ref. 8); also clearly associated with magnetozone representing Chron C27r in the Bottaccione section (ref. 8), but reported from lowermost part of magnetozone interpreted as Chron C26r in Hole 524 (ref. 10), Hole 527 (ref. 13) and from lower part of magnetozone assigned to Chron C26r in Holes 577 and 577A (ref. 9, but see text for discussion).
19. <i>Chiasmolithus danicus</i>	X		Chron C28r	63.8	1	Associated with mid part of magnetozone interpreted as Chron C28r in Holes 527 (cf. refs. 1 and 13) and 384 (ref. 1), but with lower part of magnetozone interpreted as Chron C28n in Hole 577 and 577A (ref. 9) and in the Bottaccione section (ref. 8). Associated with mid part of magnetozone representing Chron C28n in Hole 762C following Galbrun's interpretation (ref. 6) but with lower part of magnetozone representing Chron C28n following reinterpretation herein (see text).
20. <i>Cruciplacolithus tenuis</i>	X		Chron C29n	64.5	1	Associated with the mid to lower third of magnetozone interpreted as Chron C29n in Holes 527 (refs. 1, 13), 762C (cf. refs. 6 and 14), 577 (ref. 9); with basal magnetozone representing Chron C29n in the Contessa Highway Section (ref. 8), but reported from magnetozone interpreted as Chron C29r in Hole 738 (ref. 16).
21. <i>Cruciplacolithus primus</i>	X		Chron C29r	64.8		Slightly below the magnetic polarity reversal interpreted as the Chron C29n/C29r boundary in Holes 762C (cf. refs. 5 and 13), 527 (refs. 1, 13) and 577 (ref. 9).
22. <i>Hornibrookina teuriensis</i>	X		Chron C29r	64.9		Restricted to southern high latitudes. Slightly below the magnetic polarity reversal representing the Chron C29n/C29r boundary in Holes 738 (ref. 16) and 690C (ref. 11). Also present in lowermost Paleocene (Zone NP1b) in Hole 750 (ref. 5). LO used to define regional high latitude Zone NA2 (ref. 16).
23. <i>Biantholithus sparsus</i>	X		Chron C29r	65		First exclusively Cenozoic taxon. Occurs immediately above the K/P boundary in sections considered to be essentially continuous across the boundary such as at Sites 527 (ref. 1) and 762C (cf. refs. 6 and 13).
24. <i>Micula</i> spp.	X		Chron C29r	65	16	

¹this work²Aubry and others, 1995³Berggren and Aubry, 1995⁴Berggren and others, 1983b⁵Ehrendorfer and Aubry, 1992⁶Galbrun, 1992⁷Monechi, 1985⁸Monechi and Thierstein, 1985⁹Monechi and others, 1985¹⁰Poore and others, 1983¹¹Pospichal and Wise, 1990¹²Pospichal and others, 1991¹³Shackleton and Members of the Shipboard Scientific Party, 1984¹⁴Siesser and Bralower, 1992¹⁵Thomas and others, 1990¹⁶Wei and Pospichal, 1991¹⁷Wei and Wise, 1989¹⁸multiple references

based on data from Monechi and Thierstein (1985), Monechi and others (1985), Shackleton and others (1984) and their own data (for Site 516). Correlation between calcareous nannofossil stratigraphy (Siesser and Bralower, 1992) and the magnetostratigraphic record interpreted by Galbrun (1992) could also be used to indicate that the LO of *H. kleinelli* in ODP Hole 762C (Exmouth Plateau, eastern Indian Ocean) is located in Chron C25r. We do not comment here on the location of the LO of *H. kleinelli* in Chron C26n in the Italian sections, but we address the other reports.

Regarding the inconsistent location of the LO of *H. kleinelli* within Chron C26r, we question the reliability of the ages de-

termined by Wei and Wise (1989). Of the three sites they cite, only Site 527 allows determination of the age of the LO of *H. kleinelli* through magnetochronologic interpolation. In Hole 516F, Chron C27n was questionably identified by Berggren and others (1983b), and no normal polarity interval corresponding to Chron C26n was recovered. In addition, there are several problems (e.g., the normal polarity interval identified as Chron C25n extends from Zone NP8 to Zone NP10; thick intervals without magnetic data in Cores 81 to 85) associated with the identification of Chron C25n by Berggren and others (1983b) and with the interpretation of the NP9-NP10 zonal interval in the hole. As for the determination of the age of the LO of *H.*

kleinpelli at Site 577, we conclude from the preceding discussion that it cannot be achieved through magnetostratigraphy; Chron C27n being missing owing to a stratigraphic gap (we note in passing that the normal polarity intervals between 91.47 and 92.30 mbsf in Hole 577 and between 88.91 and 89.81 mbsf in Hole 577A (Bleil, 1985), assigned to Chron C26n by Bleil (1985) and Monechi and others (1985) are not identifiable).

Wei and Wise (1989) indicate a 1.8-my diachrony for the lowest occurrence of *H. kleinpelli* between Sites 527 and 528, a surprising fact considering that the two sites are separated by ~100 km. This important diachrony contradicts the results of Shackleton and others (1984) who, based on an inappropriate assumption/methodology, derived an age of 61.6 Ma for the LO of *H. kleinpelli* in Hole 528, equal to the age they determined for this event in Hole 527. Hole 528 has a very poor magnetostratigraphic record and poor recovery. Zone NP6 was not determined in the hole. It may or may not occur in the interval of no recovery between 343 and 350 mbsf (Core 25–2 to Core 26–1). Chron C25r is represented as a thin sliver of sediments in Core 24–3, but the sediments below yield no magnetostratigraphic information down to Core 30 (Chron C28n). It can be seen that it is an incorrect procedure to determine the age of a datum based on an assumed stratigraphic position in a section through extrapolation from a magnetic reversal (Chron C25n/C25r in Core 24) to a level where there is no magnetic signal. The claim that the LO of *H. kleinpelli* is associated with Chron C25r in Hole 528 is thus invalid.

Integration of magneto- and biostratigraphy in Hole 762C (Galbrun, 1992) indicates that the NP5/NP6 zonal boundary (LO of *H. kleinpelli*) occurs in Chron C26r. However, the lowest reported occurrence of *H. kleinpelli* in the hole (Siesser and Bralower, 1992) lies in an interval of unknown polarity slightly below a reversed polarity interval assigned by Galbrun to Chron C25r. There is a 7-m uncertainty as to the exact location of the LO of *H. kleinpelli* (between Core 32-CC and Core 33-1) due to poor recovery, and possibly for the same reason, a normal polarity interval corresponding to Chron C26n was not recovered. Galbrun (1992) assigned the thick interval of predominantly reversed polarity in Core 29–3 to Core 32–2 to Chron C25r. Four thin normal polarity events occur in this interval, and we note that the three upper ones that cluster around 443 mbsf (Core 31, sections 1–3) are immediately below the LO of *Discoaster mohleri* and correlate with the upper part of Zone NP6. Although we recognize that these three thin normal events have weak magnetization intensity and are represented by single points, we suggest that they represent Chron C26n based on their close association with the NP6/NP7 zonal boundary. Alternatively, Chron C26n was not identified because of the recovery gap in Core 30. This nevertheless establishes that the LO of *H. kleinpelli* in Hole 762C is in Chron C26r. Except for the reports on the two Italian sections, the LO of *H. kleinpelli* most probably lies in Chron C26r at all sites considered.

The two examples discussed above and discussions on the upper Paleocene and lower Eocene Series (Aubry and others, 1995), the lower and middle Eocene Series (Aubry, this volume), and the Neogene System (Aubry, 1991, 1993a, b) indicate that stratigraphic sections must be submitted to great scrutiny before the relationships between (paleontologic, magnetic, isotopic) events can be established and used for the purpose of magnetobiochronology. We emphasize, however, that although

we believe that unconformities are more widespread in the stratigraphic record than once thought, we do not deny that diachrony of several millions of years occurs. But diachrony of low amplitude (<2 my) can only be demonstrated once the completeness of the sections that are compared has been established, and from the “remarks” in Tables 14 to 17 it can be deduced that most claims for small latitudinal diachrony are not warranted.

Discrepancies in magnetobiostratigraphic correlations between sections are also sometimes the result of differences in taxonomic concepts. This can be seen in particular for the Eocene taxon *Reticulofenestra umbilicus* in which large changes in size occur. Although size is not a good specific criteria for calcareous nannoplankton species, size is often used by specialists to differentiate taxa. It may also be that a confusion of 5-rayed morphotypes of *Discoaster lodoensis* with *D. sublodoensis* when overgrowth occurs, accounts for the discrepancies in the correlation between the lowest occurrence of *D. sublodoensis* and the magnetic reversal pattern (see Table 15, Item 18). Although the role of differences in taxonomic concepts is probably limited for Paleogene markers, it may be substantial for other taxa (e.g., *Ericsonia subpertusa* whose LO is given as low as NP1 and as high as NP5), thus reducing the number of taxa useful to construct a magnetobiochronologic framework.

The limiting factor in this compilation remains the lack of quality of the magnetobiostratigraphic correlations in many sections, due to poor recovery in some sections, or/and to the ambiguity or insufficient quality of the magnetic polarity signal in others. For example, poor recovery in Holes 527, 528, 577 limits considerably the interpretation of the Paleogene sections (see Aubry, this volume, for Sites 527 and 528), and prevents tying a datum event to a precise level in a reversal, while ambiguous magnetic patterns in Hole 516F (see Table 15 and Aubry, this volume) prevents a confident tie between middle Eocene datums and magnetic reversals. Ambiguous magnetic records in many Oligocene sections have led to unwarranted descriptions of latitudinal diachrony (see below). Thus there is an uncertainty of variable importance (<50,000 yr to >200,000 yr) in the age estimates proposed here. Also, these impediments reduce the use of other valuable markers in constructing a biochronologic framework (e.g., *Sphenolithus furcatholithoides*, *S. obtusus*, *Cruciplacolithus delus*), a situation well reflected by the low number of datums for the middle Eocene Series which contrasts with the fact that this was the time of greatest diversity in the Cenozoic (Aubry, 1992a). We point out that we use LO and HO in Tables 14 to 17, as strictly stratigraphic terms meaning respectively “lowest occurrence” (not “last occurrence”) and “highest occurrence”, in contrast with FAD and LAD, terms with temporal significance.

Paleocene Epoch.—Twenty four Paleocene datums are established. Few Paleocene sections with reliable magnetobiostratigraphic correlations are currently available, either due to poor recovery (e.g., Hole 762C) or to the presence of unconformities (e.g., Holes 577, 577A). Although it may eventually yield presently undeciphered unconformities, DSDP Site 384 appears to offer the greatest completeness between Chron C25n and C29n. DSDP Site 527 is another quite complete section but precise magnetobiostratigraphic correlations are difficult to establish because of poor recovery.

TABLE 15.—EOCENE CALCAREOUS NANNOFOSSIL MAGNETOCHEMISTRY. SEE TABLE 14 FOR EXPLANATION.
EOCENE

Datum	FAD	LAD	Paleomagnetic Chron	Age in Ma	Reference	Remarks
1. <i>Discoaster saipanensis</i>	X		Chron C13r in low-mid latitudes	34.2	1,12	This datum is clearly diachronous between low-mid latitudes and southern high latitudes:
			Chron C16n in southern high latitudes	35.4	33	<i>Low-mid latitudes</i> : Lower part of magnetozone corresponding to Chron C13r in Massignano (ref. 12) and Contessa Highway (cf. refs. 19 and 25) sections; Lower part of magnetozone representing Chron C13r (ref. 1) but upper part of it (ref. 22) in Hole 522 LAD claimed to be younger in Hole 516F (30° S) than in Contessa Highway section (43°N) (ref. 34) but magnetostratigraphic record in Hole 516F for the Chron C13n to C16r interval is very poor, magnetozones representing Chrons C15n and C16n being very thin (ref. 8) and unconformities are suggested. LAD claimed to be younger at Site 528 than at other localities (ref. 34). HO of <i>D. saipanensis</i> immediately below the magnetozone interpreted as Chron C13r in Hole 528, but sediments are assigned to planktonic foraminiferal Zone P15 to P16 immediately underlying Zone P18 (ref. 11) which implies a stratigraphic gap.
2. <i>Discoaster barbadiensis</i>	X		Chron C13r in low-mid latitudes	34.3	2,21	<i>Southern high latitudes</i> : HO in lowermost magnetozone interpreted as Subchron C16n.1n in Hole 744A (ref. 33) and within magnetozone assigned to Chron C16n in Hole 748B (ref. 3).
			Chron C18n in southern high latitudes	~39	3	<i>Low-mid latitudes</i> : HO at the same level as HO of <i>D. saipanensis</i> (lower third of magneto zone representing Chron C13r) in Massignano (ref. 12) and Contessa Highway (refs. 19, 25) sections, but slightly below HO of <i>D. saipanensis</i> in expanded oceanic sections such as Hole 522 (ref. 22) and Hole 612 (ref. 21). Same comments as for <i>D. saipanensis</i> regarding diachrony of the LAD of this taxon between Sites 527, 528, 516 and Contessa Highway section (ref. 34).
3. <i>Reticulofenestra reticulata</i>	X		Chron C15r in mid-low latitudes	35	6,21,25	<i>Southern high latitudes</i> : HO within magnetozone representing Chron C18n (through indirect correlation) in Hole 749 (ref. 3).
			Subchron C16n.2n at southern high latitudes	36.1	33	This datum clearly diachronous between low-mid latitudes and southern high latitudes:
4. <i>Reticulofenestra oamaruensis</i>	X	X	Subchron C16n.1n	35.4	32	<i>Low-mid latitudes</i> : HO in mid magnetozone representing Subchron C16n.1n in the Massignano section (ref. 12) but near the magnetic polarity reversal corresponding to the Chron C15n/C15r boundary in the Contessa Highway section (ref. 25) and in Hole 522 (ref. 6; not in C15n as shown in refs. 34 and 35). Has been tied to Chron C15n in Hole 516F (ref. 34), but the paleomagnetic data (ref. 8) are insufficient to warrant this correlation. See also discussion in ref. 21.
						<i>Southern high latitudes</i> : HO in magnetozone interpreted as Chron C16n in Holes 689 and 690B (ref. 35), 744A (ref. 33), 748B (ref. 3) and 703A (ref. 32; we agree with Wei (ref. 32) that the normal polarity interval between 130.70 and 136.55 mbsf in Hole 703A represents Chron C16n rather than Chron C15n in Hailwood and Clement (1991b). Diachrony occurs, but is not as large as suggested in reference 2.
5. <i>Isthmolithus recurvus</i>	X		Subchron C16n.2n	36	25,33	Just below (between 130.80 and 132.30 mbsf) the magnetic polarity reversal interpreted as the Chron C15r/C16n boundary (at 130.70 mbsf) in Hole 703A (ref. 32; see additional comment regarding identification of Chron C16n in Item 3). This species is restricted to southern high latitudes
						Mid part of magnetozone representing Chron C15n (ref. 14) but upper part of magnetozone assigned to Chron C15r (ref. 25) in the Contessa Quarry section. Uppermost part of magnetozone representing Chron C16n (ref. 12) but at the magnetic polarity reversal corresponding to the Chron C15r/C16n boundary (ref. 15) and upper part of magnetozone assigned to Subchron C16n.2n (ref. 25) in the Contessa Highway section. Basal part of magnetozone corresponding to Chron C15r in the Bottaccione section (ref. 15) but mid part of magnetozone interpreted as Subchron C16n.2n in the Massignano section (ref. 25). Mid upper part of magnetozone assigned to Chron C15r (ref. 22) but at least as low as upper part of magnetozone interpreted as Chron C16n (ref. 6) in Hole 522A. Not delineated because of a recovery gap (ref. 23) but as low as magnetozone interpreted as Chron C17n (ref. 6) in Hole 523. Tied to latest Chron C17n in Hole 516F (ref. 34) but uncertainty in the magnetostratigraphic record in the hole (ref. 8) does not warrant this claim. Mid part of magneto zone interpreted as Subchron C16n.2n in Hole 744A (ref. 33); Mid part of magnetozone assigned to Chron C16n in Holes 703A (ref. 32), 748 (ref. 3), 689 and 690 (ref. 35); Polarity chronozone C16n is truncated by an unconformity in Hole 689 (refs. 28, 30) so that it is misleading to suggest that the LO of <i>I. recurvus</i> is older at Site 689 (64°S) than at Site 690 (65°S) as done in ref. 35. See also discussion in ref. 21.

TABLE 15.—Continued.
EOCENE

Datum	FAD	LAD	Paleomagnetic Chron	Age in Ma	Reference	Remarks
6. <i>Chiasmolithus oamaruensis</i>	X		Subchron C17n.1n	37	23	Located in magnetozone interpreted as Subchron C17n.1n in Hole 523 (ref. 23; the species was recorded from a single level which likely corresponds to its FAD since this level is immediately above the HO of <i>C. grandis</i> , a relationship seen in many middle-upper Eocene sections). Located in magnetozone assigned to Chron C17n in Holes 689 (ref. 35) and 748 (ref. 3); indeterminate position in Hole 516F (ref. 34; large uncertainty in the magnetostratigraphic record), and in Hole 690 (ref. 35; Polarity Chronozone C17n is truncated by an unconformity which also truncates the lower range of <i>C. oamaruensis</i> in the hole (refs. 28, 30, 35). Based on these remarks, it is clear that the claim that the FO of <i>C. oamaruensis</i> is diachronous with latitude (refs. 34, 35) is unsubstantiated.
7. <i>Chiasmolithus grandis</i>	X		Subchron C17n.1n	37.1	23	Located in magnetozone assigned to Subchron C17n.1n in Hole 523 (refs. 6, 23). Tied to Chron C17n in Hole 516F (ref. 34) but location imprecise because of large uncertainty in the magnetostratigraphic record in the hole with neither the Chron C17n/C17r nor C16r/C17n boundaries delineated (see ref. 8). Mid part of magnetozone assigned to Chron C18n in the Bottaccione section but lowermost part of magnetozone interpreted as Chron C18n in the Contessa Highway section (cf. refs. 15 and 19) and upper part of magnetozone assigned to Chron C18n in the Contessa Quarry section (ref. 14). However no magnetozone representing Chron C17n was recorded from the Bottaccione section (ref. 18). We note the same relationship between the HO of <i>C. grandis</i> and the LO of <i>G. semiinvoluta</i> in this section and in Hole 516F (cf. refs. 8 and 26). In this latter the 2 events are closely associated with Polarity Chronozone C17n. <i>Chiasmolithus grandis</i> does not occur in southern high latitudes.
8. <i>Reticulofenestra bisecta</i>	X		Subchron C17n.3n	38	20,23	Tied to Polarity Chronozone C17n.3n in Hole 523 (cf. refs. 20 and 23). Lower part of magnetozone interpreted as Chron C18n in the Contessa Highway section and mid part of magnetozone assigned to Chron C18r in the Bottaccione section (ref. 15). The relationship between the LO of <i>R. bisecta</i> and Polarity Chronozone C17r in Hole 523 supports the suggestion (Item 7) of a miscorrelation between normal polarity intervals and seafloor anomalies in the Italian sections around the Chrons C19n–C16n interval.
9. <i>Chiasmolithus solitus</i>	X		Chron C18r	40.4	23	Tied to upper Polarity Chronozone C18r in Hole 523 (ref. 23). Tentatively within Polarity Chronozone C18n in Hole 748 (ref. 3). Because of discontinuous occurrence, HO in Hole 516F is difficult to determine. Given in Polarity Chronozone C18n (ref. 34) but may be better located in Polarity Chronozone C18r (using ref. 8). Possibly Polarity Chronozone C17r in Hole 689 (ref. 35). Cannot be located in Hole 690B (contrary to ref. 35) owing to a stratigraphic gap which truncates the upper range of <i>C. solitus</i> (refs. 28, 30).
10. <i>Reticulofenestra reticulata</i>			Chron C19r	42	24,28,30	Mid Polarity Chronozone C19r in Hole 689 (based on data in refs 24 and 28, and contrary to ref. 35 which places this LO in mid Chronozone C18n). Given in mid Chronozone C18n in Hole 690B (ref. 35) but falls in a reversed interval (ref. 28) assigned to Chron C19r (ref. 30) in this hole. Falls at a magnetic polarity reversal interpreted as the Chron C19n/C18r boundary in Hole 516F (refs. 34, 35) but magnetostratigraphic succession in this section (ref. 8) is unclear and polarity chronozone assignments were mostly tentative between Polarity Chronozones C20n and C18n.
11. <i>Nannotetrina fulgens</i>	X		Chron C20r	43.1	9,23	Mid Polarity Chronozone C20n in Hole 523 (ref. 23). Given in Polarity Chronozone C19r in Hole 516F (ref. 34) but see comments regarding item 13. In the epicontinental sediments of the Hampshire Basin, the HO of <i>N. fulgens</i> is in lower Zone NP16 (above the HO of <i>B. gladius</i> , ref. 2)
12. <i>Blackites gladius</i>	X		Chron C20n	43.4	2,4,34	Tied to Polarity Chronozone C19n in Hole 516F (ref. 34). However magnetostratigraphic pattern in Hole 516F is unclear between Polarity chronozone C20n and C18n (ref. 8). Data from ref. 3 suggest that the normal polarity interval interpreted as Chron C19n in ref. 8 may best be identified as Chron C20n. If that is correct, the LO of <i>B. gladius</i> is tied to early Chron C20n, in agreement with magnetobiostratigraphic correlations in the Bracklesham beds of the Hampshire Basin (ref. 2 and Aubry and others, 1986).

TABLE 15.—Continued.
EOCENE

Datum	FAD	LAD	Paleomagnetic Chron	Age in Ma	Reference	Remarks
13. <i>Reticulofenestra umbilicus</i>	X		Chron C20n	43.7	9,15,19	Located at the magnetic polarity reversal interpreted as the Chron C20n/C20r boundary (refs. 15, 19) but in the mid part of the magnetozone interpreted as Chron C20r (ref. 14) in the Contessa Highway section. Polarity Chronozone C19r in Hole 528 (ref. 23). Mid part of magnetozone interpreted as Chron C19r in Hole 523 (ref. 6, based on >14µ specimens as established in ref. 7). Upper part of magnetozone interpreted as Chron C20n in Hole 516F (ref. 34, using the >14µ size limit). See further comments in ref. 9.
14. <i>Chiasmolithus gigas</i>	X		Chron C20r	44.5	4,9,34	Mid part of magnetozone interpreted as Chron C19r in Hole 516F (ref. 34) but in the upper third of magnetozone interpreted as Chron C20r in this hole based on reinterpretation of the magnetostratigraphy following data in ref. 4 (see also Item 13); upper part of magnetozone assigned to Chron C20r in Hole 523 (ref. 23)
15. <i>Chiasmolithus gigas</i>	X		Chron C20r	46.1	4,9,34	Slightly above magnetozone assigned to Chron C21n in Hole 516F (ref. 34). Not delineated (base of hole) in lower Polarity Chronozone C20r or below in Hole 523 (ref. 23).
16. <i>Nannotetraena fulgens</i>	X		Chron C21n	47.3	9,15	Mid Polarity Chronozone C21n in the Bottaccione and Contessa Highway sections (ref. 15). See also comments in ref. 9 and interpretations of various middle Eocene sections from the Atlantic Ocean (ref. 4).
17. <i>Blackites inflatus</i>	X		Chron C21r	48.5	9,15	Upper Polarity Chronozone C21r in the Bottaccione section (ref. 15).
18. <i>Discoaster sublodoensis</i>	X		Chron C22n	49.7	9,15	Lower Polarity Chronozone C22n in the Contessa Highway section, but Polarity Chronozone C22r in the Bottaccione section (ref. 15). Mid Polarity Chronozone C22n in Hole 530A (cf. refs. 13 and 29, see also ref. 4); upper Polarity Chronozone C22n in Hole 577 (ref. 16)
19. <i>Tribrachiatus orthostylus</i>	X		Chron C22r	50.6	4,9	Lower Polarity Chronozone C22r in the Bottaccione section (ref. 15). Mid to lower Polarity Chronozone C22r in Holes 550 and 549 (cf. refs. 17 and 31; see also ref. 4), Holes 528 and 527 (ref. 27; see also ref. 4).
20. <i>Discoaster lodoensis</i>	X		Subchron C24n.2r	52.85	4,9	Mid Polarity Chronozone C24n in the Bottaccione section (ref. 15). Polarity Subchronozone C24n.2r in Holes 549, 550 and in Hole 530 (cf. respectively refs. 17 and 31 and refs. 13 and 29; see also ref. 3 for discussion).
21. <i>Tribrachiatus contortus</i> Morphotype B	X		Chron C24r	53.61	5,10	see text
22. <i>Tribrachiatus orthostylus</i>	X	X	Chron C24r	53.64	5,10	see text
23. <i>Tribrachiatus bramlettei</i>			Chron C24r	53.89	5,10	see text
24. <i>Tribrachiatus contortus</i> Morphotype B	X		Chron C24r	53.93	5,10	see text
25. <i>Tribrachiatus contortus</i> Morphotype A		X	Chron C24r	54.17	5,10	see text
26. <i>Tribrachiatus contortus</i> Morphotype A	X		Chron C24r	54.37	5,10	see text

¹This work²Aubry, 1983³Aubry, 1992⁴Aubry, this volume⁵Aubry and others, 1995⁶Backman, 1987⁷Backman and Hermelin, 1986⁸Berggren and others, 1983b⁹Berggren and others, 1985b¹⁰Berggren and Aubry, 1995¹¹Boersma, 1984¹²Coccioni and others, 1988¹³Keating and Herrera-Bervera, 1984¹⁴Lowrie and others, 1982¹⁵Monechi and Thierstein, 1985¹⁶Monechi and others, 1985¹⁷Müller, 1985¹⁸Napoleone and others, 1983¹⁹Nocci and others, 1986²⁰Percival, 1984²¹Poag and Aubry, 1995²²Poore and other, 1982²³Poore and others, 1983²⁴Pospischal and Wise, 1990²⁵Premoli Silva and others, 1988a²⁶Pujol, 1983²⁷Shackleton and others, 1984²⁸Spies, 1990²⁹Steinmetz and Stradner, 1984³⁰Thomas and others, 1990³¹Townsend, 1985³²Wei, 1991³³Wei and Thierstein, 1991³⁴Wei and Wise, 1989³⁵Wei and Wise, 1990

Latest Paleocene-earliest Eocene Epochs.—The complexity of the stratigraphic relationships between paleontologic events and magnetic events around the Paleocene/Eocene boundary have been unravelled, implying the extensive development of unconformities in deep-sea and shallow water sections around the Paleocene/Eocene boundary (Aubry and others, 1995). The intricacies involved in tying a magnetostratigraphic and a chronostratigraphic framework (Cande and Kent, 1992, 1995) and the lack of (magnetic) resolution in the long Chron C24r interval have resulted in an unsatisfactory magnetostratigraphic framework for the latest Paleocene-earliest Eocene Epochs. This is discussed at length in Aubry and others (1995) and Berggren and Aubry (1995). We point to the fact that there is

as yet no firm magnetostratigraphic calibration for *Discoaster diastypus*.

Eocene Epoch.—Twenty five datums are established. Some are tentative because of insufficient documentation of their relationship to magnetic stratigraphy. The poorest documented datums are the FAD of *Blackites inflatus* (largely due to widespread unconformities around the lower/middle Eocene boundary (Aubry, this volume), the LAD of *Blackites gladius* (largely due to its restriction to epicontinental areas), the LAD and the FAD of *Chiasmolithus gigas* (largely due to ambiguous interpretation of the magnetic record in sections where the species occurs). Their age estimates are somewhat arbitrary.

Although Hole 762C represents an expanded Eocene section, it has not been used in this compilation because the magnetic reversals identified by Galbrun (1992) on the basis of numerical succession need to be reinterpreted. Regardless of Galbrun's interpretation, the magnetobiostratigraphic correlations in the site appear to be rather ambiguous.

Oligocene Epoch.—Magnetobiochronology in the Oligocene Epoch is difficult to achieve because of the complexity of the reversal pattern, particularly after Chron C9, and because of biogeographic provincialism, many Oligocene marker species being excluded from the southern high latitudes as a result of progressive middle Eocene cooling and subsequent early Oligocene individualization of a southern water mass (see review in Aubry, 1992a). At these latitudes, identification of the upper Oligocene reversal pattern is mostly dependant upon pattern matching without the benefit of the firm biostratigraphic control established at mid-low latitudes. This results in weak high-latitude magnetobiostratigraphic correlations which do not sustain the patterns of diachrony of paleontologic events described by some (e.g., Wei, 1991, 1992; Wei and Wise, 1992).

A case in point concerns the HO of *Chiasmolithus altus* reported by Wei (1992, p. 162) to "have a fairly consistent age of ~26.7 Ma in the Southern Ocean except in the extreme high latitudes where the datum appears to be substantially younger." Wei (1992, Fig. 8) shows that the HO of *C. altus* is very near the Chron C7Ar/C8n boundary at DSDP Site 516 (30°S), in Chron C7Ar at ODP Sites 699 (52°S) and 748 (58°S), in Chron C8n at Site 744 (62°S), at least as young as Chron C7n at Site 689 (65°S) but in Chron C10n at Site 690 (65°S).

The HO of *C. altus* in Hole 516F is located between Cores 13–1 and 13–2 (Wei and Wise, 1989; however, we note the discontinuous occurrence of the species above Core 17–3). This falls in an interval with poor paleomagnetic control between upper Core 12 and lower Core 15, bracketed by two thin normal intervals. Berggren and others (1983b) identified the upper normal polarity interval as Chron C7An, assigned the lower one to Chron C8 and located the Chron C7A/C8 boundary at the lower boundary of the upper normal. Thus, if anything, the HO of *C. altus* in Hole 516F is located in Chron C8n or C8r, not in Chron C7Ar or at the Chron C7A/C8n boundary (unrecovered in the hole). Considering the insufficient magnetic control and the ambiguous correlation between planktonic foraminiferal and calcareous nannofossil stratigraphy in Hole 516F (Berggren and others, 1983b), it is only safe to conclude that the HO of *C. altus* at Site 516 is likely associated with Chron C8.

Wei (1991) located the HO of *C. altus* in mid Chron C7Ar (between Cores 15H-5 and 16H-1) at Site 699. Firstly, we note that direct correlation between magneto- and biostratigraphy in Hole 699A (Hailwood and Clement, 1991a; Wei, 1991) does not allow such precise location. Due to incomplete recovery in Core 15, the Chron C7An/C7Ar boundary was not delineated in the hole. Secondly, we question the interpretation of the upper Oligocene magnetic reversal stratigraphy. As noted by Hailwood and Clement (1991a), there are few biostratigraphic constraints to correctly identify the magnetic reversals in Hole 699A, and these authors relied heavily on the FAD of *Roccella gelida* to this end. Using an age estimate of 26 Ma for the FAD of this diatom species, derived from Fenner (1984) through implied and indirect correlation to the then as yet unpublished chronology of BKF85, they assigned the reversed polarity in-

terval in the lower part of Core 14 and the upper part of Core 15 to Chron C7r, and consequently determined the normal polarity interval in lower Core 15 to Chron C7An, the reversed polarity interval in upper Core 16 to Chron C7Ar, and the underlying normal polarity interval in Core 16 to Chron C8n. Different extrapolated age estimates have been given for the FAD of *R. gelida* (Fenner, 1984; Barron, 1985), and as indicated above, the age estimate by Fenner (1984) has served for an inferred correlation between the FAD of *R. gelida* and Chron C7r (Cieselski and others, 1988). However, the first available direct magnetobiostratigraphic correlation in Hole 744A shows that the FAD of *R. gelida* falls in lower Chron C8n (Baldauf and Barron, 1991), indicating that the normal polarity interval in Core 15H (Hole 699A) represents Chron C8n rather than Chron C7An. Hence, the HO of *C. altus* in Hole 699A is associated with Chron C8n, just as it is in Hole 744A (Wei and Thierstein, 1991).

The HO of *C. altus* at Site 748 is located by Wei (1991) in Chron C7Ar (and apparently slightly younger than at Site 699). There are several problems associated with this correlation. First, it is difficult to determine the highest occurrence of *C. altus* in Hole 748B because there is an abundance change above Core 9H-6 (Aubry, 1992b; Wei and others, 1992) and there is no *a priori* reason to suspect that *C. altus* is reworked above this level. In any case, the HO of *C. altus* in Hole 748B (and of all other associated species in Core 9, including *R. bisecta*, see, Table 16, Item 2) has little stratigraphic significance since no *in situ* Paleogene calcareous nannofossil assemblages are preserved in this hole above Core 9 (Aubry, 1992b). Second, if a straightforward correlation is established between calcareous nannofossil (Aubry, 1992b) and magnetostratigraphy following the interpretation by Inokuchi and Heider (1992), the HO of *C. altus* in Hole 748B falls in Chron C6r (following Aubry, 1992b) not in Chron C7Ar (following Wei and others, 1992). Second, the magnetostratigraphic record in Hole 748B is ambiguous and every reversal was interpreted as corresponding to a different chron by Inokuchi and Heider (1992). The lowest occurrence of *R. gelida* lies in Core 10 in Hole 748B (Schlich and others, 1989) indicating that the normal polarity interval between ~77 and ~85 mbsf in the hole corresponds to Chron C8n. This is in agreement with Harwood and Maruyama (1992, Fig. 16) who inferred from diatom stratigraphy the presence of an unconformity in the lower part of Core 9H with a hiatus encompassing the younger part of Chron C8n to mid Chron C7n. The change in abundance of *C. altus* indicated above occurs on both sides of the unconformity (from abundant to common above, see Aubry, 1992b, Table 3, and from abundant to rare, see Wei and others, 1992, Table 3). We thus interpret the presence of *C. altus* above it as reflecting intensive reworking (reworking of *C. altus* and other Paleogene taxa occur throughout the Neogene section in Hole 748B) and conclude that the range of *C. altus* is truncated in Hole 748B, and that there is poor evidence that the species ranges higher than Chron C8n.

Because the upper range of *C. altus* is truncated in Holes 689B and 690B, Wei (1991) concluded that the HO of *C. altus* is younger than "25.6 Ma and 26.6 Ma at these two sites respectively" (1991, p. 159). This corresponds to a correlation with Chron C7n or younger at Site 689 and with Chron C7Ar or younger at Site 690, although Wei (1991, Fig. 8) shows a correlation with the Chron C10n/C10r boundary. We note that

TABLE 16.—OLIGOCENE CALCAREOUS NANNOFOSSIL MAGNETOCHRONOLOGY. SEE TABLE 14 FOR EXPLANATION.
OLIGOCENE

Datum	FAD	LAD	Paleomagnetic Chron	Age in Ma	Reference	Remarks
1. <i>Reticulofenestra bisecta</i>		X	Subchron C6Cn.2r	23.9	21	Located in mid part of magnetozone interpreted as Chron C6Cn in Hole 522 (refs. 1, 16); in magnetozone interpreted as Subchron C6Cn.2r at Site 703 (47° S; ref. 21); just below the magnetic polarity reversal interpreted as the Chron C6Cn/C6r boundary in Holes 563 and 558 (ref. 12) but Chron C6Cn is represented by only two normal polarity intervals in these holes. Given in mid Polarity Chronozone C6Cn in Hole 516F (and slightly younger than at Sites 522, 558 and 563; refs 21, 23) although we do not understand this determination, Wei and Wise (ref. 23, p. 134) indicating the presence of a hiatus encompassing most of Chrons C6Cn and C6Br. Shown as being younger (in Subchron C6Cn.2r) at Site 748 (58° S) than at any other southern latitude sites (Ref. 21, 25). This is however not supported by diatom stratigraphy (ref. 9) which indicates that the upper range of <i>R. bisecta</i> is truncated by an unconformity in Hole 748B (see Item 6 for discussion). Shown to be slightly older (in Subchron C6Cn.3n) at Site 699 (52° S) than at Site 516 (ref. 21) but magnetostratigraphic record in Hole 699A is ambiguous and does not allow this claim. HO of <i>R. bisecta</i> in Holes 744A (ref. 22), 689A and 690B (ref. 24) not recorded due to unconformities. Thus the claim that the LAD of <i>R. bisecta</i> is not reliable at extreme southern high latitudes (ref. 21) is inappropriate.
2. <i>Sphenolithus delphix</i>	X		Chron C6Cr	24.3	12	Upper Polarity Chronozone C6Cr in Hole 563 (ref. 12)
3. <i>Zygrhablithus bijugatus</i>		X	Chron C6Cr	24.5	12	Located in lower magnetozone assigned to Chron C6Cr in Holes 558 and 563 (ref. 12); indeterminate position in Polarity Chronozone C6Cr in Hole 516F because of insufficiently detailed magnetic record (cf. refs. 5 and 23)
4. <i>Sphenolithus ciperoensis</i>	X		Chron C6Cr/C7n	24.75	19	Tied to latest Chron C7n in Holes 522 (refs. 1, 16; however, the polarity reversal representing the Chron C6Cr/C7n boundary is located at a core break), 558 and 563 (ref. 12), and 608 (ref. 6; but the Polarity Chronozone C6Cr/C7n boundary is not delineated in the hole, ref. 7). Probably associated with Polarity Chronozone C7n in Hole 516F (cf. refs. 5 and 23) but insufficient magnetostratigraphic control does not allow greater detail. Located in lowest part of magnetozone representing Chron C6Cr in Hole 528 (ref. 19, but Chron C7n is represented by only one (thin?) normal polarity interval in this hole, see ref. 1, Fig. 3) and in the Contessa Highway section (ref. 11). The quality of the magnetostratigraphic records in Holes 558, 563, 522, 528 and 516F does not allow a precise comparison between geographic locations of the HO of <i>S. ciperoensis</i> with respect to Chron C7n as done by Wei and Wise (ref. 23, Fig. 21).
5. <i>Chiasmolithus altus</i>	X		Chron C8n	26.1	22	Located in upper Polarity Chronozone C8n in Hole 744A (ref. 22). Located in basal Polarity Chronozone C8r in Hole 522 (cf. refs. 15 and 16). This record provides the only indication that the LAD of <i>C. altus</i> may be diachronous between low-mid and high southern latitudes. See text for other reported correlations to the magnetic record.
6. <i>Sphenolithus umbrellus</i>	X		Chron C9n	~27.5	12	Indeterminate position in Polarity Chronozone C9n in Hole 563 (ref. 12).
7. <i>Sphenolithus distentus</i>	X		Chron C9n	27.5	1,16	Located in magnetozone interpreted as Chron C9n (ref. 16) but as Chron C7n (ref. 23, Fig. 20) in Hole 522. <i>Sphenolithus distentus</i> is sporadic in Hole 522 but it is clearly reworked above Core 20 (i.e., in the Polarity Chronozone C7n-C8r interval in the hole) as indicated by its discontinuous occurrence (ref. 1). Located in a reversed polarity interval above Polarity Chronozone C9n in Hole 528 (ref. 23) if the magnetic reversal at 182.06 mbsf in the hole represents the top of Polarity Chronozone C9n as interpreted by Shackleton and others (ref. 19). However, confident identification of the reversed polarity interval is not possible: following Shackleton and others's interpretation the stratigraphic interval representing Chron C7n to Chron C11n(y) is only 19.40 m, which corresponds to an unlikely sedimentation rate of $0.3 \text{ cm}/10^3 \text{ yr}$. Instead we suggest that the interval between 170.96 and 190.36 mbsf in Hole 528 comprises one or more unconformities. Located in an interval of unknown magnetic polarity bounded by normal polarity intervals in Hole 516F (ref. 23) assigned to polarity Chronozone C9n (ref. 5). However, this interpretation of the magnetostratigraphic record in Hole 516F is questionable (see Item 11). Tied to earliest Chron C10n in Hole 558 (ref. 12), but see comments at Item 9. Precise position of the HO of <i>S. distentus</i> with respect to magnetostratigraphy at different geographic locations as proposed by Wei and Wise (ref. 23) is not acceptable considering the uncertainty in the magnetic stratigraphy at these locations .

TABLE 16.—Continued.
OLIGOCENE

Datum	FAD	LAD	Paleomagnetic Chron	Age in Ma	Reference	Remarks
8. <i>Sphenolithus predistentus</i>	X		Chron C9n	27.5	1	Closely associated with the HO of <i>S. distentus</i> in many sections but the stratigraphic succession of the 2 events is variable. Located in Polarity Chronozone C9n in Hole 522 (slightly below the HO of <i>S. distentus</i> , refs. 1, 16). HO of <i>S. predistentus</i> below that of <i>S. distentus</i> in Hole 516F where it is located in an interval of unknown magnetic polarity bounded by 2 normal polarity intervals (ref. 23) interpreted as Chron C9n (ref. 5). However, this interpretation of the magnetic reversal stratigraphy in Hole 516F is questionable (see Item 11). Located in Polarity Chronozone C10n, (slightly above the HO of <i>S. distentus</i>) in Hole 558 (ref. 12), but the magnetostratigraphic succession in the hole is unclear between Polarity Chronozones C7n and C11n and it may be that either the interval assigned to Chron C10n by Miller and others (ref. 12) represents Chron C9n, or that an unconformity occurs just above it. The magnetobiostratigraphic record in this hole cannot serve to evaluate possible diachrony of the LAD of <i>S. distentus</i> and <i>S. predistentus</i> .
9. <i>Sphenolithus pseudoradians</i>	X		Chron C10r	29.1	16	Mid Polarity Chronozone C10r in Holes 522 (ref. 16) and 558 (ref. 12)
10. <i>Sphenolithus ciperoensis</i>	X		Subchron C11n.2n	29.9	1	Located in Polarity Subchronozone C11n.2n (refs. 1, 15) but in Subchronozone C10n.2n (ref. 16) in Hole 522; in Polarity Subchronozone C11n.2n in Hole 558 (ref. 12). Located in Polarity Chronozone C11n in Hole 528 if the normal polarity interval between 190.36 and 201.36 mbsf in the hole is identified as Chronzone C11n rather than as Chronozones C11n and C12n concatenated as proposed by Shackleton and others (ref. 19). LO not paleomagnetically constrained in Hole 563 (ref. 12) because of lack of magnetic record contrary to Wei and Wise (ref. 23). Falls in an interval of unknown polarity (in Core 19) bounded by normal polarity intervals in Cores 19 and 20 in Hole 516F (ref. 23), assigned to Chron C9n (ref. 5). However, because of insufficient magnetic control with almost no reversed polarity intervals delineated in the Polarity Chronozone C7A-C11n interval in the hole, this correlation may be erroneous. Also, the correlation between planktonic foraminifera and calcareous nannoplankton biozones in Hole 516F (ref. 5) is problematic, and there is no overlap of the ranges of <i>S. distentus</i> and <i>S. predistentus</i> with that of <i>S. ciperoensis</i> in Hole 516F unlike in other sections. This may indicate the absence of Zone NP24 (unconformity) as an alternative explanation to the diachrony of the LAD of <i>S. ciperoensis</i> suggested by Wei and Wise (ref. 23).
11. <i>Sphenolithus distentus</i>	X		Chron C12r	31.5 to 33.1	17,23	Located in upper Polarity Chronozone C12r in the Contessa Highway section (refs. 14, 18) and in Hole 523 (ref. 17); in mid Polarity Chronozone C12r in Hole 522 (refs. 1, 16); in lower Polarity Chronozone C12r in Hole 563 (slightly lower than the HO of <i>E. formosa</i>) and in Hole 558 (at a level between the HO of <i>E. formosa</i> and that of <i>R. umbilicus</i> ; ref. 12); in lower Polarity Chronozone C13n in Hole 516F (ref. 23).
						This is a very inconsistent datum which may occur as low as Zone NP21 (e.g., Sites 516, 563, Oceanic Formation, Barbados), in Zone NP22 (e.g., Site 558) or as high as in Zone NP23 (e.g., Contessa Highway section and many DSDP/ODP sites).
12. <i>Reticulofenestra umbilicus/ R. hillae</i>	X		early Chron C12r in low-mid latitudes late Chron C12r in southern high latitudes	32.3 31.3	1,12 22	This datum is clearly diachronous between low-mid latitudes and southern high latitudes: <i>Low-mid latitudes:</i> Located in lower Polarity Chronozone C12r (ref. 18) or slightly above Polarity Chronozone C13n (ref. 14) in the Contessa Highway section; in lower third of Polarity Chronozone C12r in Holes 558 (ref. 12) and 523 (ref. 17); in mid part of magnetozone interpreted as Chron C12r in Hole 522 (refs. 1, 3, 16). Indeterminate position in Polarity Chronozone C12r in Hole 563 (ref. 12); located slightly above magnetic polarity reversal corresponding to the Chron C13n/C12r boundary in Hole 516F (ref. 23) but this boundary is poorly delineated in the hole (ref. 5). Given in Polarity Chronozone C12r in Hole 528 (ref. 23 using ref. 19). However, we suggest that the normal polarity interval between 190.36 and 201.36 mbsf in Hole 528 corresponds to Chron C11n (see Item 11) rather than to the concatenation of Polarity Chronozones C11n and C12n as interpreted by Shackleton and others (ref. 19). Also, Chron C13n is poorly characterized in Hole 528 and sampling in the interval between 201.36 mbsf (polarity reversal N to R) and 221.83 mbsf (polarity reversal R to N) is insufficient to confidently characterize Chron C12r (see ref. 13, Fig. 3). <i>Southern high latitudes:</i> Located in upper Polarity Chronozone C12r in Holes 690B (ref. 24), 744A (ref. 22), 748 (refs. 2 (but misprinted in Fig. 3, cf. refs 2 and 10), 23), and 703A (ref. 21); in uppermost Polarity Chronozone C12r in Hole 699A (ref. 21) where Chron C12r is poorly characterized due to insufficient sampling (ref. 9) and in Hole 689B (refs. 21, 24) where the magnetic record is also ambiguous, with Chronozone C11r considerably thinner than Chronozone C12n following Spiess's interpretation (ref. 20) which would result in sedimentation rates of 0.56 cm/10 ³ yr for the mixed calcareous and siliceous sediments (ref. 4) representing Chron C12n.

TABLE 16.—Continued.
OLIGOCENE

Datum	FAD	LAD	Paleomagnetic Chron	Age in Ma	Reference	Remarks
13. <i>Isthmolithus recurvus</i>		X	Chron C12r	31.8 to 33.1	16,22	One of the most inconsistent datums. Falls in upper Polarity Chronozone C13n in Hole 522 (ref. 16); in lowermost Polarity Chronozone C12r in the Contessa Highway section (ref. 18); in lower Chronozone C12r, between the HO's of <i>R. umbilicus</i> and <i>E. formosa</i> in Hole 523 (ref. 17); in lower Chronozone C12r at the same level as the HO of <i>R. umbilicus</i> in Hole 558 (ref. 12); in Chronozone C12r at the same level as the HO of <i>R. umbilicus</i> in Hole 563 (ref. 12); slightly above mid Chronozone C12r in Hole 744A (ref. 22), in upper Chronozone C12r (ref. 2 but misprinted in Fig. 3, cf. refs. 2 and 10) but in mid Chronozone C12r (ref. 25) in Hole 748B. Given in lowermost Chronozone C12r in Hole 516F (refs. 21, 23) but the Chronozone C12r/C13n boundary is poorly characterized in this hole (ref. 5); given in mid Chronozone C12r (ref. 21) in Hole 699A, but falls in an ~15 m thick interval without magnetic data (ref. 8) and the Chronozone C12r/C13n boundary is not delineated in the hole; given in mid Chronozone C12r in Hole 689B (ref. 21) but identification of Chronozone C12n in this hole is questionable; given in mid Chronozone C12r in Hole 690B (ref. 21) but precise location cannot be determined as the Chronozone C12r/C13n boundary was not recovered due to an unconformity (ref. 20).
14. <i>Ericsonia formosa</i>		X	Chron C12r in mid-low latitudes Chron C18 in southern high latitudes	32.8 ~39.7	1,3 2,20,24	This datum is clearly diachronous between low-mid and high southern latitudes: <i>Low-mid latitudes:</i> Located in uppermost Chronozone C13n (ref. 14) but immediately above Chronozone C13n (ref. 18) in the Contessa Highway section. Located in lowermost Chronozone C13n in Hole 558 (ref. 12), in lower Chronozone C12r in Holes 522 (refs. 1, 3, 16), 523 (ref. 17), 528 (ref. 19, but see remarks regarding Item 13) and Hole 747C (ref. 2). Given in upper Chronozone C13n in Hole 516F (ref. 23) but the Chronozone C12r/C13n boundary is poorly characterized in this hole (ref. 5). <i>High southern latitudes:</i> HO associated with polarity Chronozone C18 (through indirect correlation) in Holes 748C and 749 (ref. 2) and possibly in Hole 689B (cf. refs. 20 and 24). There is no magnetic stratigraphy in Holes 748C and 749, and the magnetostratigraphic record is insufficiently documented in Hole 689B to allow a more precise location in Chronozone C18 of this event.
15. <i>Clausicoccus subdistichus</i>	Acme		Chron C13n	33.3	18	Located (= <i>Ericsonia obruta</i>) in lower Chronozone C13n in the Massignano section (ref. 18).
16. <i>Reticulofenestra oamaruensis</i>		X	Chron C13r	33.7	22	Located in uppermost Chronozone C13r in Holes 744A (ref. 22), 748B (ref. 25), 689B (ref. 24), and possibly at the Chronozone C13n/C13r boundary in Hole 699A (ref. 21, Fig. 4). This species is restricted to southern high latitudes.

¹This work²Aubry, 1992b³Backman, 1987⁴Barker and others, 1988⁵Berggren and others, 1983b⁶Clement and Robinson, 1987⁷Gartner, 1992⁸Hailwood and Clement, 1991a⁹Harwood and Maruyama, 1992¹⁰Inokuchi and Heider, 1992¹¹Lowrie and others, 1982¹²Miller and others, 1985¹³Moore, and others, 1984¹⁴Nocci and others, 1986¹⁵Percival, 1984¹⁶Poore and others, 1982¹⁷Poore and others, 1983¹⁸Premoli Silva and others, 1988a¹⁹Shackleton and others, 1984²⁰Spiess, 1990²¹Wei, 1991²²Wei and Thierstein, 1991²³Wei and Wise, 1989²⁴Wei and Wise, 1990²⁵Wei and others, 1992

these correlations are strictly dependant upon the interpretation of the magnetic reversal succession in the holes by Spiess (1990) who noted in particular the lack of biostratigraphic constraints below the unconformable Oligocene/Miocene contact at 67 mbsf in Hole 689B. Spiess (1990) derived a chron assignment in the upper Oligocene section in Hole 689 through upwards extrapolation from Chron C18 to C10 to the unconformity based on a depth/age curve. Spiess (1990) remarked that this curve indicates constant sedimentation rates and does not provide evidence of hiatuses in the interval considered. However, he failed to notice the extraordinarily low sedimentation rates ($\sim 0.1 \text{ cm}/10^3 \text{ yr}$) resulting from his interpretation,

a rate incompatible with the lithology of these upper Oligocene sediments (diatom-rich calcareous nanofossil oozes, Kennett, Barker and others, 1988). The lowest occurrence of *R. gelida* is located in lower Chron C8n in Hole 744A (Baldauf and Barron, 1991). In Hole 689B, it is located between Cores 8H-4, 74–76 cm and 8H-5, 74–76 cm (Kennett and others, 1988a) or in Core 8H-6 (Gersonde and Burckle, 1990; i.e., in the upper part of the normal polarity interval identified by Spiess, 1990, as Chron C8n). On this basis, we suggest that this interval corresponds to Subchron C8n.2n, that the interval of primarily reversed polarity that Spiess (1990) assigned to Chron C7r and C7A may represent Subchron C8n.1r, and that the normal po-

larity interval immediately below the unconformity at 67 mbsf (Chron C7n in Spiess, 1990) represents part of Subchron C8n.1n.

The situation is similar in Hole 690B. Spiess (1990) assigned the polarity intervals below the unconformable Oligocene/Miocene contact at 51 mbsf in Hole 690B to Chron C7Ar, Chron C8 and Chron C9. Whereas Spiess (1990, p. 292) noted that "Subchron C11n between 72 and 74 mbsf is extraordinarily short in comparison to C11r" (and interpreted by him as indicative of a stratigraphic gap encompassing the upper part of Chron C11n), Spiess did not remark on the similarly remarkably thin interval representing Chron C8r that results from his interpretation. We suggest that the magnetic reversal succession was not correctly interpreted by Spiess (1990). The LO of *R. gelida* is located in Core 7H-3 (Gersonde and Burckle, 1990) which indicates that the reversed polarity interval in Core 7H-1, 100–102 cm to Core 7H-2, 124–126 cm likely corresponds to Subchron C8n.1r. If these reinterpretations are correct, Holes 689 and 690 do not provide evidence that at the extreme southern high latitudes, the HO of *C. altus* is younger than Chron C8n.

This review shows that there is no firm evidence that the HO of *C. altus* is diachronous across latitudes with diachrony increasing with increasing latitude. However, there may be slight (~ 1 my) diachrony between low-mid and high southern latitudes, as suggested by the different magnetobiostratigraphic correlations at southern high-latitude sites (in Chron C8n) compared to Site 522 (in Chron C8r; cf. Percival, 1984; Poore and others, 1982).

The review of the reliability of other datums in Table 16 shows that the situation is similar for many other taxa. In particular, we point to the fact that the magnetobiostratigraphic records in many sections (discussed in Table 16) do not allow the precise chronologic ties between paleontologic datums and magnetic reversals shown by some (Wei, 1991, 1992; Wei and Wise, 1989, 1990, 1992; Wei and others, 1992). These records are not clean and detailed enough to support comparisons between sections at the resolution of 10,000 to 100,000 yr claimed by these authors. Discrimination of 200,000 yr for any datum between sections should already be regarded questionable. Thus the claim of progressively increasing diachrony with increasing latitude is considered unwarranted for most datums at this time (see Table 16, Items 9 to 11 in particular). There are, however, datums that are diachronous between low-mid and southern high latitudes. This is the case of *Reticulofenestra umbilicus/R. hillae* (two close morphotypes that are treated as one species herein for convenience) and *Ericsonia formosa*. The former disappeared earlier from the low-mid latitudes than from the southern latitudes, whereas the latter disappeared very early from the southern latitudes. The diachrony involved is ~ 1 my for *R. umbilicus* and perhaps as much as 7 my for *E. formosa* and is likely directly linked to water mass evolution rather than to a latitudinal (temperature) effect.

A few datums with chronologic potential that needs to be explored are tentatively given (e.g., FAD and LAD of *Sphenolithus umbrellus*; LAD of *S. pseudoradians*). Altogether 16 Oligocene datums are discussed.

Neogene Period.—

Miocene Epoch.—Although many Miocene sections have been drilled by DSDP/ODP, few sections have yielded a magneto-

biostratigraphic record of sufficient quality from which to derive a reliable calcareous nannofossil biochronology. The Miocene calcareous nannofossil chronology in BKVC85 relied heavily on the magnetobiostratigraphic correlations at DSDP Site 516 (for the early and late Miocene; Berggren and others, 1983b), 558 and 563 (for the middle Miocene; Miller and others, 1985), and to a lesser extent on DSDP Sites 519 and 521 (for the middle and late Miocene; Poore and others, 1983). The best sections subsequently recovered are from DSDP/ODP Sites 608 (Olafsson, 1991; Gartner, 1992), 710 (Backman and others, 1990; Rio and others, 1990), 711 (Rio and others, 1990) and more recently from ODP leg 138 Sites 844, 845, 848, 852 and 853 (Raffi and Flores, 1995; Raffi and others, 1995). The magnetostratigraphic record at some of the ODP Leg 138 sites is of excellent quality (Mayer and others, 1992; Schneider, 1995), thus allowing exceptionally precise ties between biostratigraphic and magnetostratigraphic events (Raffi and Flores, 1995; Raffi and others, 1995). There remain, however, inconsistencies between the correlations established from these sites and those in other sections. The synchrony of biostratigraphic events is currently being challenged by most specialists, and despite the fact that excellent synchrony (with a resolution better than 50,000 yr) has been demonstrated for some Pliocene markers (Backman and Shackleton, 1983), the consensus remains that diachrony is widespread among calcareous nannofossils accounting for different magnetobiostratigraphic correlations at different locations. As for the Paleogene Period we do not share this view and would argue that undeciphered unconformities of regional extent are a greater impediment than diachrony in constructing a biochronologic framework.

There are several problems specific to Miocene magnetostratigraphy. Firstly, the polarity reversal pattern is far more complex than for any interval in the Paleogene System, with a high reversal frequency. While this increases the potential for greater chronologic resolution, it also makes the interpretation of the magnetostratigraphic record difficult unless the magnetic reversal stratigraphy is of excellent quality. Comparison between the two interpretations given of the upper middle Miocene magnetostratigraphic record in Hole 563 by Miller and others (1985) and by Miller and others (1994) illustrates well the seriousness of the problem. Secondly, whereas the integration of calcareous nannofossil and planktonic foraminiferal stratigraphy with magnetostratigraphy is particularly critical for interpreting Miocene sections, many DSDP/ODP sections suffer from the lack of correlations between the two microfossil groups. This is the case in particular for the Indian Ocean and the equatorial Pacific sites. Thirdly, some of the magnetobiostratigraphic correlations proposed here are based on a single record or on magnetic records that are less than straightforward, and there is a certain amount of circular reasoning involved in revising polarity interval identification based on newer but ambiguous magnetobiostratigraphic correlations (as for instance in Hole 563, Miller and others, 1994, see below). For these reasons, we believe that Miocene biochronology will still undergo major changes. Progress in isotope stratigraphy will help in improving the temporal interpretation of stratigraphic sections (e.g., Wright and Miller, 1992; Miller and others, 1994), but even so, pattern matching between isotopic peaks can be deceiving as exemplified in Aubry and others (1995). A particularly difficult interval is the upper middle Miocene Series

(Zones NN8-NN10; Zones N15-N16). The problem is very complex and involves the stratigraphic relationships between several calcareous nannofossil (see Table 17, Items 9 to 15) and planktonic foraminiferal species. In particular, the relationships among the LOs of *Discoaster hamatus*, *Catinaster calyculus*, *Neogloboquadrina acostaensis* and *N. mayeri*, and between these and the magnetic polarity record vary between sections (see discussion in BKVC85, Aubry (1993a), Berggren (1993) and Tables 13, 17). This has been differently interpreted as reflecting diachrony (Miller and others, 1994) or unconformities (Aubry, 1993a, b), but there is no definitive evidence at this time to support one or the other explanation. The difficulty is exacerbated by the fact that, contrary to Miller and others's (1994) claim of a dichotomy between tropical and subtropical late middle and early late Miocene markers, no clear pattern in the inconsistencies emerges which would support diachrony (see Table 17). We thus provide, when necessary, two alternative sets of correlation between calcareous nannofossil events and magnetic reversals (Table 17).

Another difficult relationship to establish is that between the LAD of *S. heteromorphus* and the magnetic reversal polarity. This LAD was tied to Chron C5ADn and given an estimated age of 14.4 Ma in BKF85, based on the polarity record in Hole 563 (Miller and others, 1985). A revised age estimate of 13.6 Ma was subsequently proposed by Backman and others (1990) based on Site 710 where the datum occurs in an interval without interpretable magnetic polarity record due to slumping. The validity of this inexplicit revision (in an interval which displays numerous slumps) was emphasized by Backman and others (1990), because of the apparent agreement between the magnetobiostratigraphic correlation (with Chron C5ABr) inferred from this age and that directly established in Hole 608. We caution that despite the apparently straightforward magnetobiostratigraphic record in Hole 608 (Gartner, 1992), the magnetic polarity pattern is no less ambiguous in this hole than in Holes 563 and 558 (Miller and others, 1985). The normal polarity intervals interpreted as Chrons C5ADn and C5ACn (Clement and Robinson, 1987) are anomalously thin (and thinner than Chrons C5AA and C5ABn) in Hole 608, and Chron C5ACr was not recovered possibly due to no recovery in lower Core 33. However, identification of the reversal pattern between Cores 34 and 31 is strictly based on numerical succession, assuming stratigraphic completeness and accepting tremendous variations in rates of sedimentation at this location. Miller and others (1994) followed the magnetic interpretation in Hole 608 and reinterpreted the magnetic reversal pattern in Hole 563. We agree with their assignment to Chron C5AA of the normal polarity interval originally ascribed to Chron C5ACn (Miller and others, 1985), but do not support their reassignment to Chron C5AB-C5AD of the normal polarity interval initially assigned to Chron C5AD-C5B (Miller and others, 1985). If the LAD of *S. heteromorphus* is located in Chron C5ABr following Gartner (1992), the upper part of this latter normal polarity interval can only represent Chron C5ACn or older. This indicates the absence of Chron C5ABn in Hole 563. Considering the ambiguous magnetic polarity record in Hole 608 around the Chrons C5AB-C5AD interval, it seems reasonable to await confirmation from another magnetobiostratigraphic record to firmly establish the age of the LAD of *S. heteromorphus*. Recent magnetobiostratigraphic correlations in the central Paratethys Basin

(Steininger and others, 1995) show that the Badenian/Sarmatian (sensu Suess) boundary lies within calcareous nannofossil Zone NN6 and correlates with Chron C5ABr at 13.6 Ma which supports an older age of the LAD of *S. heteromorphus*.

Following Raffi and Flores (1995), we incorporate the recently defined subzonal interval which corresponds to the total range of *Amaurolithus amplificus* in the reference biostratigraphic frameworks of Okada and Bukry (1980) and Martini (1971). We also tentatively include a few datums that are very useful for lower Miocene stratigraphy but are poorly tied to the magnetic polarity record. We prefer to refrain from citing datums which are stratigraphically very useful (e.g., HO of *Discoaster neohamatus*, LO of *D. pentaradiatus*, *D. surculus*, LO of *Helicosphaera ampliaperta*, see Gartner and others, 1983; Aubry, 1993a, b) but which may not be satisfactorily tied to the magnetic scale. We do not believe that the LAD of *Triquetrorhabdulus carinatus*, one of Martini's (1971) zonal markers, has yet been satisfactorily tied to the magnetic polarity reversal. Thirty Miocene datums, most of which were considered by Gartner (1992), Raffi and Flores (1995) and Raffi and others (1995), are further discussed here (Table 17).

Pliocene and Pleistocene Epochs.—For calcareous nannofossil chronology in the Pliocene and Pleistocene Epochs, we refer the reader to the work of Berggren and others (1995).

The biozonal criteria and the duration of the Paleocene to upper/late Miocene biozones/biochrons based on Martini's (1971), Bukry's (1973, 1975) and Okada and Bukry's (1980) zonal schemes are summarized in Figures 17 to 22.

CHRONOSTRATIGRAPHY

Paleogene Period

A revised geochronology for the Paleogene Period based on the integration of calcareous plankton biostratigraphic data to the revised magnetochronology of CK92/95 has been presented above in Figures 1 (Paleocene), 2 (Eocene) and 3 (Oligocene) with corresponding chronology of the (sub)tropical planktonic foraminiferal datum events used to delineate zonal boundaries shown in Figures 8, 9 and 10, respectively, and the chronology of calcareous nannofossil zonal boundaries shown in Figures 17 to 19. In this section, we discuss (predominantly post-1985) biostratigraphic data relevant to identification and correlation of the limits and extent of Paleogene chronostratigraphic units.

The terms Paleogene and Neogene are used here as period/system subdivisions of the Cenozoic Era/Erathem. The term Tertiary is considered, like the other antiquarian subdivisions of earth history (Primary, Secondary and Quaternary), as inappropriate, if not "obsolete" (GTS89; p. 3). A thorough discussion of Paleogene chronostratigraphic terminology and recommended usage was presented in BKF85 (see also Berggren, 1971). Discussion here is limited to aspects of Paleogene chronostratigraphy requiring elaboration or modification in the context of the revised geochronology adopted here.

The Cretaceous/Paleogene boundary is located within the younger part of Chron C29r with an estimated age (CK92) of 66.0 Ma and 65 Ma (CK92/95; adopted here). The age estimate in CK92 was based upon a "compromise" between problems current at that time in obtaining consistent radioisotopic isotopic ages for the K/P boundary (see discussion by Swisher in

TABLE 17.—MIOCENE CALCAREOUS NANNOFOSSIL MAGNETOCHRONOLOGY. SEE TABLE 14 FOR EXPLANATION.
MIOCENE

Datum	FAD	LAD	Paleomagnetic Chron	Age in Ma	Reference	Remarks
1. <i>Discoaster quinqueramus</i>	X		Mid Chron C3r	5.6	16,17,19	HO tied to mid Chron C3r in Holes 710, 844, and to late Chron C3r in Holes 845 and 854 (refs. 16, 17).
2. <i>Amaurolithus amplificus</i>	X		Chron C3r/C3 An.1n boundary	5.9	16,17	HO tied to the Chron C3r/Subchron C3An.1n boundary in Holes 844 and 853, and to mid Subchron C3An.1n in Hole 845 (refs. 16, 17).
3. <i>Amaurolithus amplificus</i>	X		Subchron C3An.2n/ Chron C3 Ar boundary	6.6	16,17	LO tied to the Subchron C3An.2n/Chron C3Ar boundary in Holes 844 and 853 (refs., 16, 17).
4. <i>Amaurolithus primus</i>	X		Subchron 3Br.2r	7.2	16,17	LO tied to mid Subchron C3Br.2r in Holes 710, 844, 845, 848 (although only the early part of Chron C3Br is represented in the hole) and 853 (refs. 16, 17).
5. <i>Discoaster loeblichii</i>	X		Chron C4n/C3Br	7.4	16,17	Tied to latest Chron C4n in Hole 744 but to mid Chron C4n in Hole 853 (refs. 16, 17); to early Chron C3A in Hole 608 (ref. 8), but the Subchron C3An.2n/C3Ar boundary is not delineated in the hole.
6. <i>Minylitha convallis</i>	X		Subchron C4n.2n	7.8	16,17	HO slightly below the LO of <i>A. primus</i> in many sections including cores from the Gulf of Mexico (refs. 2, 9), Indian Ocean Sites 709 and 710 (ref. 18) and equatorial Pacific Sites 844 and 845 (refs. 16, 17). HO tied to late Subchron C4n.2n in Holes 710, 844, 854 (refs. 16, 17); HO tied to Chron C4n in Holes 698 (ref. 10) and 848 (refs. 16, 17).
7. <i>Discoaster berggrenii</i>	X		Subchron C4r.2r	8.6	16,17	We agree with Raffi and Flores (ref. 16) that <i>D. berggrenii</i> and <i>D. quinqueramus</i> are distinct morphotypes of the same taxon, with slightly different ranges. LO tied to earliest Chron C4r.2r in Holes 710, 844, 845 and 848 (refs. 16, 17); to late Chron C4n in Hole 608 (ref. 8) but we note the anomalously close proximity of this LO and the LO of <i>A. primus</i> in this hole.
8. <i>Discoaster loeblichii</i>	X		Chron 4r/C4An boundary	8.7	16,17	LO tied to the Chron C4r/C4An boundary in Hole 844 (refs. 16, 17) and to late Chron C4An in Hole 608 (ref. 8).
9. <i>Discoaster bollii</i>	X		Atlantic-Caribbean realm: Subchron C4Ar.1r	9.1	8,10	Given in Chronozone C4Ar.2r in Holes 844 and 710 at a position similar to that in Holes 563 and 608 (ref. 17). However, in Holes 844 and 710, the HO of <i>D. bollii</i> is immediately above the LO of <i>D. hamatus</i> (ref. 17) whereas in Holes 563 (ref. 10) and 608 (ref. 8), in several cores from the Gulf of Mexico (ref. 2) and in the Buff Bay section, Jamaica, (ref. 1), the two events are well separated. The magnetic polarity record is insufficient to locate precisely in Chronozone C4Ar the HO of <i>D. bollii</i> in Holes 563 and 608, but it is more appropriately located in the upper part than in the lower part of the chrono zone. We tentatively tie the LAD of <i>D. bollii</i> to Subchron C4Ar.1r in the Atlantic-Caribbean realm where this event is younger than the LAD of <i>D. hamatus</i> and the FAD of <i>M. convallis</i> . (see item 10).
10. <i>Minylitha convallis</i>	X		Equatorial Pacific: Subchron C4Ar.1n	9.3	16,17	LO juxtaposed with the HO of <i>D. hamatus</i> in Chronozone C4Ar.2r in Hole 710 (refs. 16, 17). LO considered restricted in the equatorial Pacific Ocean compared to the tropical Indian Ocean (ref. 17). At equatorial Pacific Sites 844 and 848, its LO, well into Zone NN10, is well above the HO of <i>D. hamatus</i> and located in Subchronozone C4Ar.1n (refs. 16, 17). We point out that in several cores from the Gulf of Mexico, the LO of <i>M. convallis</i> is consistently found well above the HO of <i>D. hamatus</i> (ref. 2), as in the equatorial Pacific cores, and this corresponds well with the range given by Bukry (ref. 6) for this species. Also, in the Gulf of Mexico cores and in the Buff Bay section, Jamaica, there is a substantial overlap of the ranges of <i>D. bollii</i> and <i>M. convallis</i> (refs. 1, 2) whereas in Holes 710 and 844, the LO of the latter is immediately above the HO of the former (refs. 17). Until further studies establish whether these discrepancies reflect diachrony, we tentatively propose two distinct ages for the FAD of <i>M. convallis</i> , for the equatorial Pacific Ocean, and for the Atlantic-Indian ocean regions.
11. <i>Discoaster hamatus</i>	X		Subchron C4Ar.2r	9.4	10,16,17	HO located in mid Chron C4Ar.2r in Holes 844 (but the HO is poorly defined in this hole because it is located just above a dissolution interval) and 848 (refs. 16, 17); in Chron C4Ar in Holes 608 (ref. 8) and 710 (refs. 3, 17, 18); in upper Chron C5n in Hole 563 (ref. 10). See Items 9, 10 for comments regarding the relationships between the HO of <i>D. hamatus</i> and the HO/LO of other species in different regions.

TABLE 17.—Continued.
MIOCENE

Datum	FAD	LAD	Paleomagnetic Chron	Age in Ma	Reference	Remarks
12. <i>Catinaster calyculus</i>	X		Subchron C5n.2n	10.7	10,16,17	The relationship between this datum and the FAD's of <i>C. coalitus</i> and <i>D. hamatus</i> are still poorly understood. In Hole 608 (ref. 8), in the Buff bay section, Jamaica (ref. 1), and in several Eureka cores from the Gulf of Mexico (ref. 2), the LO of <i>C. calyculus</i> falls in the upper range of <i>D. hamatus</i> (well justifying Bukry's subdivision of Zone CN7, ref. 7). In Holes 563 (ref. 10) and in Hole 710 (refs. 16, 17), the LO of <i>C. calyculus</i> is at the same level as the LO of <i>D. hamatus</i> . In Hole 714 the LO of <i>C. calyculus</i> precedes that of <i>D. hamatus</i> (ref. 17). In Hole 521A where <i>D. hamatus</i> is absent, the LO of <i>C. calyculus</i> is above the LO of <i>C. coalitus</i> and the two species co-occur for part of their ranges (ref. 20), where as in Hole 519 where <i>D. hamatus</i> is also absent, the LO of <i>C. calyculus</i> immediately follows the HO of <i>C. coalitus</i> (ref. 15). In Hole 563, the LO of <i>C. calyculus</i> is located in early Chron C5n.2n (ref. 10); in Hole 608, it is located in Chron C4Ar (ref. 8; but this may not be reliable, the species being very rare); in Hole 710, it is located below Polarity Subchronozone C5n.2n (ref. 18) although the reliability of this correlation is questioned by Raffi and others (ref. 17) owing to slumping below the normal polarity interval assigned to Chron C5n.2n. Finally, in Holes 844 and 845, the LO of <i>C. calyculus</i> is located in lower Subchronozone C5n.2n, slightly below the LO of <i>D. hamatus</i> (in a position similar to that in Hole 563).
13. <i>Discoaster hamatus</i>	X	Some locations: Subchron C5n.2n		10.7	10,11,16,17	Controversial datum. Its relationships to other datums (planktonic foraminifera as well as calcareous nannofossils) and to the magnetic polarity is highly inconsistent between sites, regardless of latitude, and is difficult to interpret because the species is absent from critical sites (e.g., Sites 519 and 521), or the magnetic polarity pattern is ambiguous (e.g., Buff Bay section, Jamaica). LO located in mid Subchronozone C5n.2n in Hole 845 and 848 (refs. 16, 17) and 608 (ref. 8) but in lower Chronozone C5n.2n in Hole 844 (refs. 16, 17). LO located in lower Subchronozone C5n.2n in Hole 563 (ref. 10), in a reversed polarity interval below Subchronozone C5n.2n in Hole 710 (ref. 18) but the validity of this correlation is questionable owing to slumping below the normal polarity interval (ref. 17). Located in an interval of primarily reversed polarity below Chronozone C5n (interpreted as Chronozone C5r.2r) in the Buff Bay section, Jamaica (ref. 11).
		Other locations: Subchron C5r.2r		11.2	11	
14. <i>Coccolithus miopelagicus</i>	X	Equatorial Pacific: Subchron C5n.2n		10.8	16,17	HO located in the younger part of Zone NN8 (ref. 1, 2, 6, 17). Located in lower Subchronozone C5r.1r in Hole 608 (ref. 8), but in lower Subchronozone C5n.2n in Holes 844 and 845 (where it is clearly below the LO of <i>D. hamatus</i>) and in mid Subchronozone C5n.2r in Hole 848 (where it is juxtaposed with the LO of <i>D. hamatus</i> ; refs. 16, 17).
15. <i>Catinaster coalitus</i>	X	Equatorial Pacific: Subchron C5n.2n		10.9	16,17	One of the most controversial Miocene datums because of inconsistent correlations to the magnetic polarity record. There are currently two sets of magnetobiostratigraphic correlations: 1) FAD located in early Chron C5n.2n as determined from Hole 608 (ref. 12; but if so, LO anomalously above the HO of <i>C. miopelagicus</i> in the hole, see ref. 8 and Item 14), 519 (ref. 15), 521A (ref. 20), and 845 (ref. 16, 17). The position of the FAD is not constant in the chron, but varies from early Chron C5n.2n as in Hole 519 (ref. 15) to earliest Chron C5n.2n as in Hole 845 (ref. 17). 2) the FAD is located in Chron C5r at a moment that remains uncertain because of insufficient magnetic records. This is seen in Hole 563 (ref. 10), 710 (ref. 17) and in the Buff Bay section, Jamaica, which yields a magnetic polarity record difficult to interpret but where the LO of <i>C. coalitus</i> is located in an interval of predominantly reversed polarity assignable to Chron C5r (ref. 11). This second correlation was followed in Berggren and others (ref. 5). Despite the excellent resolution of the magnetobiosratigraphy in the equatorial Pacific sites (refs. 16, 17), we do not believe that the conundrum has been resolved because it involves not only <i>C. coalitus</i> but several other species among calcareous nannofossils (e.g., <i>C. miopelagicus</i> , <i>D. hamatus</i> , <i>C. calyculus</i> ; see Items 12 to 14) and among the planktonic foraminifera (e.g., <i>N. acostaensis</i> , <i>N. mayeri</i> ; see Tables 12, 13). Until the reason for the discrepancy is firmly established, we provisionally propose two ages for this datum.
		Atlantic and (?) Indian Oceans: Subchron C5r.2r		11.3	10	

TABLE 17.—Continued.
MIOCENE

Datum	FAD	LAD	Paleomagnetic Chron	Age in Ma	Reference	Remarks
16. <i>Discoaster kugleri</i>	X		Subchron C5r.2n	11.5	8	Located in Polarity Subchronozone C5r.2n in Holes 608 (ref. 8) and 845 (as a common occurrence; ref. 16, 17). Raffi and Flores (ref. 16) indicate that the LAD of <i>D. kugleri</i> is in fact in Subchron C5n.2n as determined from Hole 845. Because of the discontinuous occurrence of the species in the upper part of its range in Hole 845 we question the validity of this determination. See also Item 17.
17. <i>Discoaster kugleri</i>	X		Subchron C5r.3r	11.8	8	LO in lower Subchronozone C5r.3r in Hole 845 (as common occurrence, refs. 16, 17) but in upper Subchronozone C5r.3r in Hole 608 (ref. 8). LO given in Chronozone C5AA in Hole 563 (ref. 10) based on a broad concept of the species (see ref. 1). Revised LO located in the lower reversed magnetic polarity interval in Chronozone C5 in this hole, in good agreement with Site 608.
18. <i>Triquetrorhabdus rugosus</i>	X		Chron C5AAn	13.2	8	This species is usually accorded a very short range but Raffi and Flores and Raffi and others (refs. 16, 17) indicate that this species has in fact a long range which extends from Subchron C5An.1n to C5n.2n as determined from Hole 845 (ref. 16). The species shows however discontinuous occurrence in the hole which is unfamiliar to us and the determination of Raffi and Flores (ref. 16) requires confirmation.
19. <i>Sphenolithus heteromorphus</i>	X		Chron C5ABr	13.6	8	Located in mid Chronozone C5AAn in Hole 608 (ref. 8) and at base of normal polarity interval reinterpreted as Chron C5AAn in Hole 563 (ref. 11), but in Chronozone C5Ar.1n in Hole 845 (ref. 16, 17).
20. <i>Helicosphaera ampliaperta</i>	X		Chron C5Br	15.6	8	Located in mid Chronozone C5AAn in Hole 608 (ref. 8) and at base of normal polarity interval reinterpreted as Chron C5AAn in Hole 563 (ref. 11), but in Chronozone C5Ar.1n in Hole 845 (ref. 16, 17).
21. <i>Sphenolithus heteromorphus</i>	X		Chron C5Dr	18.2	8	Located in lower Chronozone C5ABr in Hole 608 (ref. 8). Located in normal polarity interval questionably assigned to Chron C5AD in Hole 558 (ref. 10). Located in normal polarity interval assigned to Chron C5AD (ref. 10) but reinterpreted as Chron C5ABn (ref. 11) in Hole 563. This latter revised interpretation is not satisfactory however, the LAD of <i>S. heteromorphus</i> being tied to Chron C5ABr in Hole 608. At best this normal represents Chron C5ACn, and Chron C5ABn is not represented in Hole 563 (an inferred unconformity is well supported by the juxtaposition of the HO of <i>S. heteromorphus</i> and the LO of <i>T. rugosus</i> in the hole (ref. 10)).
22. <i>Sphenolithus belemnos</i>	X		Chron C5En	18.3	8	Located in lower part of Chronozone C5Br in Hole 608 (ref. 8) and in lowest Chronozone C5Br in Hole 558 (ref. 10). Associated with a thin normal polarity interval questionably assigned to Chron C5C in Hole 563 (ref. 10); however, the three normal polarity intervals in Hole 563 are very thin and poorly representative of Chron C5C.
23. <i>Triquetrorhabdulus carinatus</i>	X	?	?	?	—	Difficult datum which may not be applicable in some sections where it ranges well above the HO of <i>S. belemnos</i> (e.g., Holes 516F (ref. 4) and 710 (ref. 3)). Not recovered in Holes 558 and 563 because of a hiatus encompasses early Chron C5D to late Chron C6n (ref. 10). Cross correlations between Holes 516, 558 and 563 based on planktonic foraminifera and calcareous nannofossil do not support the magnetic polarity interpretation in ref. 4.
24. <i>Sphenolithus belemnos</i>	X		Chron C6n	19.2	8,10,18	Tied to Chron C6n in Holes 563 and 558 (ref. 10). Tied to late Chron C6n in Hole 710 (ref. 18) but Chron C5E is poorly represented in the hole. Tied to late Chron C6n in Hole 608 (ref. 8), but the HO of <i>S. belemnos</i> is located in the younger part of a normal polarity interval assigned to Chrons C6 and C6A and the magnetic reversal pattern is obscure between Chron C5E and C6B in the hole. Located in a normal polarity interval identified as Chron C5ADn in Hole 516F (ref. 4) but see comments regarding Item 22

TABLE 17.—Continued.
MIOCENE

Datum	FAD	LAD	Paleomagnetic Chron	Age in Ma	Reference	Remarks
25. <i>Sphenolithus</i> sp. aff. <i>S. belemnos</i>	X		? Chron C6Cr	—	—	Characteristic form regarded as an early morphotype of <i>S. belemnos</i> with a short spine (see ref. 2). Has its LO in mid to upper Zone NN2. LO located slightly below the normal polarity interval tentatively assigned to Chron C6An in Hole 563 (ref. 10) but interpreted here as part of Chron C6C. This datum needs to be firmly tied to the magnetic polarity pattern.
26. <i>Triquetrorhadulus serratus</i>	X		Chron C6Br	23.2	4	LO located at the same level as the LO of <i>D. druggii</i> in Hole 516F (ref. 4).
27. <i>Discoaster druggii</i>	X		Chron C6Br	23.2	4	Located in Chronozone C6Br in Holes 516F (ref. 4; but the chron C6Br/C6Cn boundary is not delineated in the hole), 558, 563 (ref. 10) and 608 (cf. ref. 8, Figs. 1, 2). FAD not in Chron C6A as in Young and others (ref. 21) based on a misinterpretation of the magnetic polarity stratigraphy in Hole 522 (ref. 15).
28. <i>Sphenolithus umbrellus</i>	X		Subchron C6Cn.Ir	23.6	10	Tied to younger normal polarity interval of Chron C6Cn in Hole 563 but Chron C6Cn is represented by only 2 normal polarity intervals in the hole (ref. 12). Tentatively correlated with mid Subchron C6Cn.Ir which makes it an earliest Miocene datum.
29. <i>Sphenolithus capricornutus</i>	X		Subchron C6Cn.2n	23.7	10	Given in Subchron C6Cn.2n (ref. 8) but see comments for item 29
30. <i>Sphenolithus delphix</i>	X		Subchron C6Cn.2n.	23.8	8,10	LAD given in Chron C6Cn.2n (ref. 8). Chron C6Cn is poorly characterized in Hole 608 and the three subchrons C6Cn.1n, 2n and 3n are undifferentiated, which precludes a precise location in Chron C6Cn.2n. In Hole 608, the HO of <i>S. delphix</i> is at the same level as that of <i>S. capricornutus</i> (ref. 8) contrary to Hole 558 (ref. 10). In Hole 563, the HO of <i>S. delphix</i> is at the same level as the HO's of <i>R. bisecta</i> and <i>S. capricornutus</i> , at the Subchronozone C6Cn/C6Cr boundary (ref. 10). However, in this hole, Chronozone C6Cn comprises only 2 normal events and the simultaneous HO's of the three species suggest the presence of an unconformity at the polarity reversal.

¹Aubry, 1993a²Aubry, 1993b³Backman and others, 1990⁴Berggren and others, 1983a⁵Berggren and others, 1985a⁶Bukry, 1973⁷Bukry, 1975⁸Gartner, 1992⁹Gartner and others, 1983¹⁰Miller and others, 1985¹¹Miller and others, 1994¹²Olafsson, 1989¹³Olafsson, 1991¹⁴Poore and others, 1982¹⁵Poore and others, 1983¹⁶Raffi and Flores, 1995¹⁷Raffi and others, 1995¹⁸Rio and others, 1990¹⁹Shackleton and others, 1995²⁰Van Salis, 1984²¹Young and others, 1994

Berggren and others, 1992, and discussion above in this paper); these ages currently range from <65 to >66 Ma.

Paleocene Series.—

The Paleocene Series consists of three stages: the Danian, Selandian and Thanetian. The Danian Stage was discussed at length by Berggren (1971) and BKF85. In BKF85, the Thanetian was considered an upper substage of the Selandian Stage with the lower substage (=lower Selandian) remaining unnamed. This is recognized as a completely unsatisfactory situation and the three units are used here in sequential order to represent the Paleocene Series. The base of (exposed) Thanetian sediments in SE England is within Chron C26n and (probably) correlative with a level in Zone NP6 (Knox and others, 1994) and corresponds to the TA2 (2.1/2.2) (56 Ma) 3rd-order cycle of Haq and others (1988). The age of the base of the Thanetian Stage is estimated at 58 Ma here. Between the top of the Danian (61.0 Ma) and the base of the Thanetian (58 Ma) are ~3 my unrepresented by an appropriate chronostratigraphic term. The Danian Stage could be extended upward to coincide with the

base of the next younger (Thanetian) stage or the Thanetian could be lowered to coincide with the top of the Danian Stage.

An alternative, and more appropriate, procedure would be to insert the Selandian Stage for the intervening stratigraphic interval between the top and base of the Danian and Thanetian Stages, respectively (and this has been now accepted by the Paleogene Subcommission on Stratigraphy). The Selandian Stage described by Rosenkrantz (1924) consists of lower (Lellinge Greensand) and middle (Kerteminde Clay) fossiliferous units and an upper ("gray unfossiliferous clay") and Holmehus unit. It lies unconformably upon the Danian Chalk Formation and contains clasts of this unit in its basal part. It is overlain, in turn, by the well known "Ash series" (=Mo Clay) which characterizes the upper part of the Holmehus and Fur/Ølst Formations. The major lithologic change from (Danian) carbonates (below) to (Selandian) clastics (above) reflects a major change in the geotectonic evolution of the NE Atlantic (i.e., marginal uplift and basinal subsidence prior to the initiation of late Paleocene sea-floor spreading in the Norwegian-Greenland Sea during Chrons C25-C26).

PALEOCENE CALCAREOUS NANNOFOSSIL BIOCHRONS

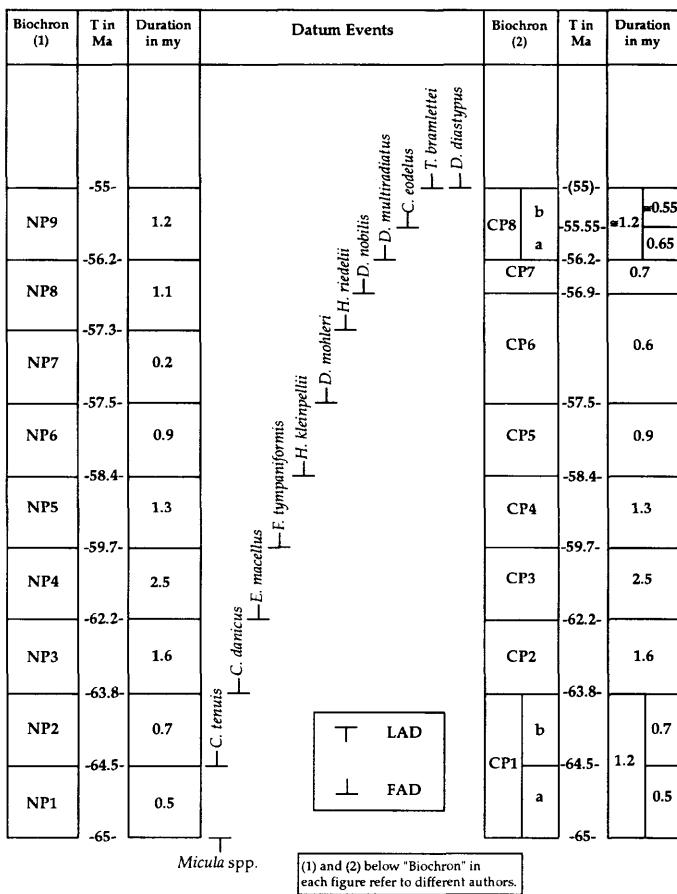


FIG. 17.—Paleocene calcareous nannofossil biochrons. (1): Following Martini's zonation (1971); (2) following Bukry's zonation (1973, 1975) and Okada and Bukry (1980). (): uncertain age due to poor calibration to the magnetic polarity record.

Integration of bio- and magnetostratigraphic studies, particularly those recently completed at DSDP Hole 384, suggests that:

1. The top of the Danian sensu stricto correlates approximately with Chron C27n(o) (estimated age: 61.2 Ma), and that of the Danian sensu lato (= Montian Stage sensu stricto) with Chron C27n(y) (estimated age 61.0 Ma; cf. earlier correlations in BKF85 and Berggren, 1994, based on suggested correlations of these levels with C27n(y) and C26r (early part)).
2. The base of the Lellinge Greensand corresponds to a level in the lower part of Chronozone C26r and to the TA1/TA2 relative coastal onlap cycle boundary of Haq and others (1988) with an age estimated here of ~60.5 Ma, whereas the Danian/Selandian boundary is (arbitrarily) placed at the Zone P2/P3 boundary (FAD of *M. angulata* and *Ig. pusilla*) with an estimated age of 61.0 Ma (Chron C27n(y); cf. Berggren, 1994, in which this level was estimated to have an age of 60.4 Ma, based on the belief that the P2/P3 zonal boundary lay in early Chron C26r). Recent data from DSDP Hole 384 have shown that the P2/P3 zonal boundary is in Chron C27n(y).

EOCENE CALCAREOUS NANNOFOSSIL BIOCHRONS

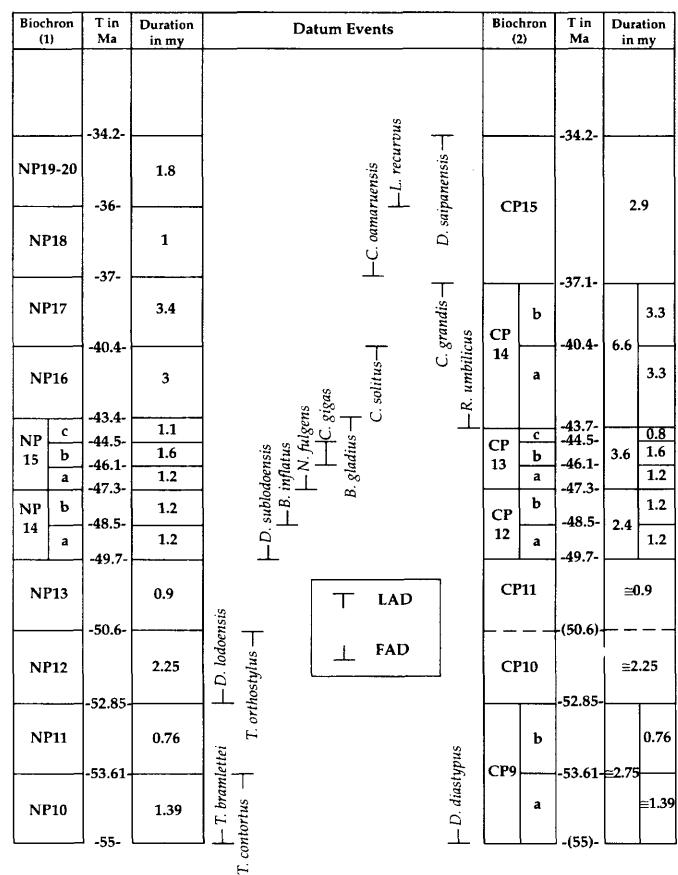


FIG. 18.—Eocene calcareous nannofossil biochrons. See Figure 17 for explanation.

3. The lower and middle parts of the Selandian Stage are stratigraphically correlative with Zones P3 and NP4-NP5 (undifferentiated) and the *Deflandrea* (vel *Cerodinium*) *speciosa* and *Palaeoperidinium pyrophorum* (dinoflagellate) Zones. The base of the latter zone is defined by the FAD of *Alisocysta margarita* which appears to be approximately correlative with the NP5/NP6 zonal boundary. The overlying *Alisocysta margarita* Zone extends to (at least) the middle part of the Holmehus Formation (Denmark), although dinocysts are generally rare in this unit, and the overlying (calcareous barren) "Gray Clay" unit belongs to the (lower) *Apectodinium hyperacanthum* Zone characterized by the earliest representatives of the wetzeliliids which become prominent biostratigraphic markers in the lower Eocene Series.
4. The base of the Thanetian Stage lies in the *Alisocysta margarita* Zone (defined by the FAD of *Deflandrea denticulata*), within Zone NP6 and is correlated with the basal part of Chronozone C26n (Knox and others, 1994) with an age estimate of 57.9 Ma here. The *A. margarita* Zone extends into mid-Thanetian levels which are referable to Zone NP8 (i.e., equivalent to the Reculver Silts but older than the Lambeth Group, formally the Woolwich-Reading series).
5. It would appear that the Selandian and base Thanetian stages overlap within the *Paleoperidinium pyrophorum* Zone (i.e.,

OLIGOCENE CALCAREOUS NANNOFOSSIL BIOCHRONS (LOW-MID LATITUDES)

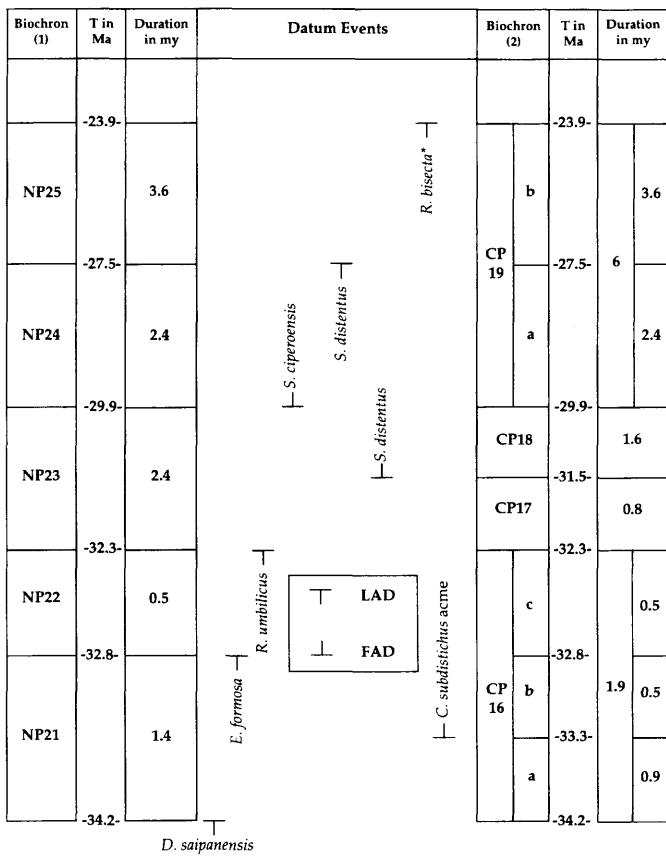


FIG. 19.—Oligocene calcareous nannofossil biochrons (for the low and mid latitudes; for ages of datum events and duration of chrons at southern high latitudes, see Table 16). See Figure 17 for explanation. *: *R. bisecta* is substituted for *H. recta*, the marker of the NP15/NN1 boundary in Martini's (1971) zonal scheme; +: end of acme.

within Zone NP6) or *Alisocysta margarita* Zone (basal Zone NP7) and at a level approximately correlative with the lower part of Zone P4 (estimated here to be only slightly older than Chron C26n(o)). When it is possible to clearly constrain the limits of these two units, it would be appropriate to formally “decapitate” the upper (predominantly un-, or sparsely, fossiliferous) part of the Selandian Stage and use the term Thanetian Stage for the remainder of the (upper) Paleocene Series.

6. The base of the Selandian Stage is ~3 my older than the base of the Thanetian Stage.
7. The hiatus between the Danian sensu stricto and the base of the Lellinge Greensand (=base Selandian Stage s.str.) is about/less than 1 my and between the Danian sensu lato and that between the base of the Lellinge Greensand is ~0.5 my.

The Selandian Stage is seen to span the entire post-Danian Paleocene Series and corresponds in its middle and upper part with the Thanetian Stage of England and to the Woolwich-Reading Beds (=Sparnacian of France). The Selandian Stage (restricted sense) can be conveniently accommodated in the Paleocene chronostratigraphic hagiography between the top of the Danian (P2 = NP4) and the base of the Thanetian Stages

EARLY AND MIDDLE MIocene CALCAREOUS NANNOFOSSIL BIOCHRONS

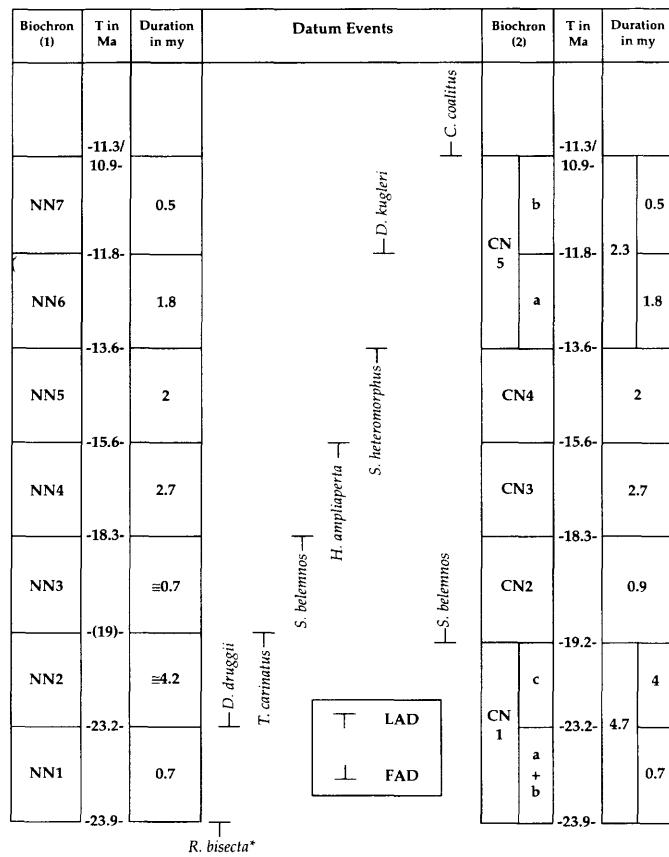


FIG. 20.—Early and middle Miocene calcareous nannofossil biochrons in the (applicable only to mid and low latitudes, the calcareous nannofossil assemblages being extremely poorly diversified at southern high latitudes). See Figure 17 for explanation. (): uncertain age due to poor calibration to the magnetic polarity record.

(=NP6, basal P4a). This approach would have the advantage of having the stratotype area (and concomitant type sections) of two successive time-stratigraphic units, the Danian and Selandian, lying in spatial continuity (i.e., in Denmark), although a distinct unconformity representing ~1-my duration separates the lithostratigraphic units of the upper Danian and lower Selandian Stages. It also results in a more appropriate three-fold chronostratigraphic subdivision of the Paleocene Series in which the temporal gap between the top of the Danian Stage sensu stricto/sensu lato and the base of the Thanetian Stage is represented (i.e., stratotypified in the rock record). A number of distinct biostratigraphic events (particularly within the dinoflagellates and perhaps within the calcareous nannofossils) can serve as biostratigraphic guideposts to delimiting the boundaries of these units in NW Europe. Hopefully the magnetostratigraphic record will provide additional, critically needed information on the position of these units within the framework of the GPTS.

Paleocene/Eocene boundary.—

The Paleocene/Eocene boundary was a focal point of controversy and discussion in our original (BKF85) and subsequent modification (Aubry and others, 1988) of the Paleogene time

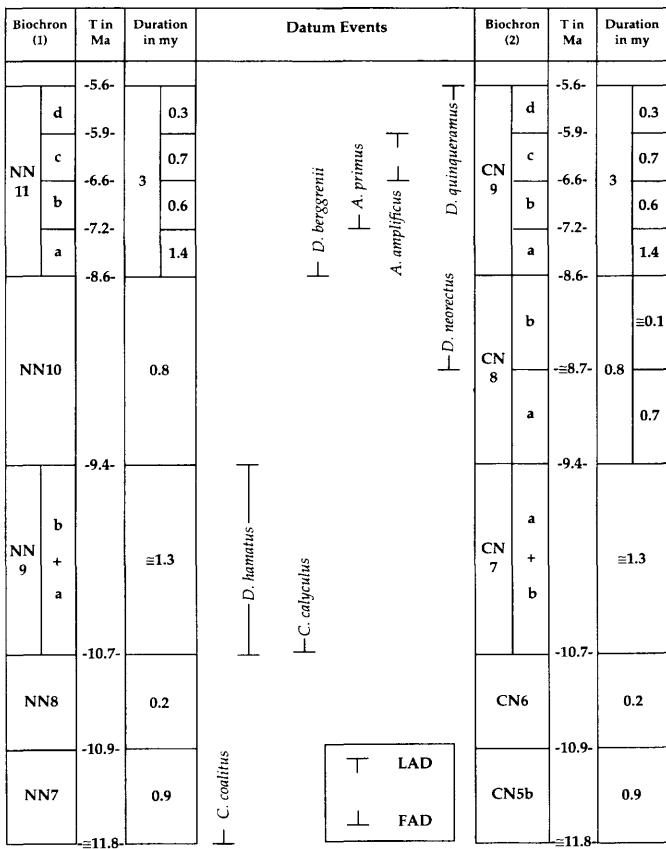
MIDDLE AND LATE MIocene CALCAREOUS NANNOFOSSIL BIOCHRONS
(equatorial Pacific)

FIG. 21.—Middle and late Miocene calcareous nannofossil biochrons, Atlantic Ocean and (?) Indian Ocean. See Figures 17 and 20 for explanation.

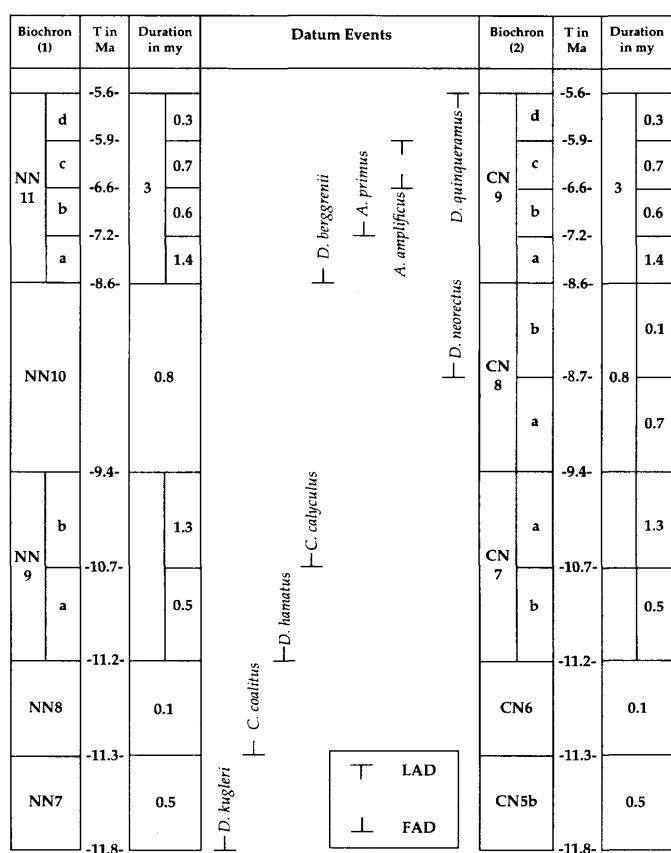
MIDDLE AND LATE MIocene CALCAREOUS NANNOFOSSIL BIOCHRONS
(Atlantic and (?) Indian Ocean)

FIG. 22.—Middle and late Miocene calcareous nannofossil biochrons, equatorial Pacific Ocean. See Figures 17 and 20 for explanation.

scale, and it remains so at the present time. Indeed, in the past few years, the jointly sponsored IUGS-UNESCO International Geological Correlation Project (IGCP) 308 “Paleocene/Eocene Boundary Events in Time and Space” has been focusing attention on the various events in the stratigraphic record that may serve to delineate (and correlate) the boundary between these two units at an as yet to be determined boundary stratotype. The subject has been discussed in considerable detail in a recent overview by Berggren and Aubry (1995) and thus only a brief summary will be presented here in the context of the time scale presented in this paper.

The Paleocene/Eocene boundary interval is located within Chron C24r, a chron with a duration of at least 2.55 my (CK92/95). Thus magnetostratigraphy is limited in this instance for more precise recognition/correlation, and other methods must be used to delineate the Paleocene/Eocene boundary (wherever it is ultimately placed) within Chron C24r. Cyclostratigraphy may be expected to aid in identifying and correlating the position of the “Golden Spike” once it has been “nailed down.”

An intricate, integrated correlation network links the base of the London Clay Formation (Ypresian Stage) with the -17 Ash Bed of Denmark and the North Sea and DSDP Hole 550 in the NE Atlantic, now dated at 55.0 Ma by Obradovich (in Berggren and others, 1992) in Denmark and at 54.5 Ma by Swisher and Knox (1991) in Denmark and offshore England to a level within

the lower part of Zone NP10 = lower CP9a and near the P5/P6 zonal boundary and to the 2.2/2.3 (TA2) 3rd-order cycle (54.5 Ma) boundary of Haq and others (1988). The estimated age of the base of the London Clay (= -17 Ash Bed) is 54.8 Ma and that of the NP9/NP10 zonal boundary 55 Ma in our chronology (see CK92/95 and discussion in Berggren and Aubry, 1995, on the methodology used in deriving these estimates). A distinct unconformity (with an estimated hiatus of ~0.5 my; Berggren and Aubry, 1995) separates the base of the London Clay Formation from the underlying Reading-Woolwich beds in SE England. While biostratigraphers often use the NP9/NP10 (calcareous nannoplankton) or the P6a/b (= P5/P6a zonal boundary of this paper; planktonic foraminifera) zonal boundary to define the Paleocene/Eocene boundary, this approach is obviously inappropriate and incorrect. A chronostratigraphic boundary is defined by a lithostratigraphic Global Stratotype Section and Point (GSSP), the so called “golden spike”, which serves to integrate and unify the correspondence between rock and time at a unique stratigraphic level. Magneto-, bio-, chronostratigraphic datum events are then used to correlate this unique level in the stratigraphic record away from the boundary stratotype area. Insofar as the Paleocene/Eocene boundary is concerned, at the present time the best we can say is that the boundary, as typified by the oldest rocks attributed to the London Clay Formation, is within Zone NP10 and near the P5/P6

zonal boundary, whereas if we refer to the Ieper Clay Formation (= Ypresian Stage of Belgium), the boundary is only slightly higher/younger. There are a large number of bio- (extinction of deep sea benthic foraminifera), chemo- ($\delta^{13}\text{C}$ isotope spike), and climato- (strong reduction in windblown aerosols) stratigraphic events associated with a level in mid-upper NP9 and P5 Zones. If the Paleocene/Eocene boundary GSSP were eventually to be placed at this level, its age would be ~ 55.5 Ma in our chronology. Suffice to say that the Paleocene/Eocene boundary lies within the stratigraphic interval bracketed by the P5/P6 zonal boundary (at ~ 54.7 Ma) and the chemo- and biostratigraphic events mentioned above which appear to occur at a level closely associated with, or slightly older than, the NP9/NP10 zonal boundary (55 Ma) and encompassing the base of the London Clay Formation (= Thanetian/Ypresian boundary) at ~ 54.8 Ma, and the NP9/NP10 zonal boundary at 55 Ma. As we have mentioned above, we have chosen not to use the radioisotopic ages of 54.5 Ma or 55.0 Ma to denote the base of the London Clay Formation, preferring to use instead estimated rates of sedimentation within the ash series in DSDP Hole 550; the reasons for this and the methods used are described in detail in Berggren and Aubry (1995).

Eocene Series.—

The Eocene Series is seen to span about 21 my in our revised chronology, essentially the same duration as that estimated in the revised chronology of Aubry and others (1988). The main difference in the two scales is, of course, the younger ages assigned to the lower and upper boundaries of the Eocene Series. The lower Eocene Series of SE England and Belgium (stratotype of the Ypresian Stage) have now been precisely correlated based on integrated litho- and magnetostratigraphic studies (Ali and others, 1993), and the base of the London Clay and Ieper Formations are now known to lie within the lower part of Chronozone C24r with age estimates of ~ 54.8 and 54.7 Ma, respectively.

Lower/middle Eocene boundary.—The lower/middle Eocene (Ypresian/Lutetian) boundary, calibrated to Chron C22n(y), is now estimated at ~ 49 Ma. Haq and others (1988) interpreted the lower Lutetian deposits of the Lutetian stratotype (at St. Leu d' Esserent, near Paris) as representing their third-order cycle TA3.1, with the Cuisian/Lutetian boundary corresponding to the 49.5 Ma sea-level fall (chronology of Haq and others, 1988). We do not agree with this interpretation inasmuch as the Cuisian/Lutetian unconformable contact reflects a stratigraphic gap which encompasses the upper part of calcareous nannofossil Zone NP12, Zone NP13, and Subzone NP14a (Aubry, 1983, 1986). The upper surface of the unconformity (= the base of the type Lutetian) lies in Subzone NP14b. Thus as discussed in Aubry (1991), the lower Lutetian Stage, would more likely represent third-order cycle TA3.2, whereas the Cuisian/Lutetian boundary reflects several offlap events, including the 49.5 Ma and the 48.5 Ma events (chronology of Haq and others, 1988).

The Lutetian/Bartonian boundary is correlated to a level within Zone NP16 and closely associated with the LAD of *Reticulofenestra reticulata* which is calibrated to Chron C19n(y) (Aubry, 1986, p. 322, Fig. 23; see also BKF85 and Haq and others, 1988, for similar placement of this boundary) with an estimate here of 41.25 Ma.

Middle/upper Eocene boundary.—The problem with the placement of the middle/upper Eocene boundary is intimately linked with the difficulties in biostratigraphic correlation between the geographically disjunct location of the upper middle Eocene Bartonian (NW Europe) and upper Eocene Priabonian (NE Italy) Stage stratotypes (see discussion in BKF85). The Bartonian Stage is assigned to Zones NP16 and NP17 (and questionably to a part of Zone NP18; Aubry, 1986), whereas the Priabonian has been assigned to Zones NP19-NP21 (Verhallen and Roem, 1983) or to NP17 (*partim*) to NP21 (*partim*; (Barbin, 1986). Brinkhuis (1992, p. 85–87, Figs. 4.2, 4.3; 1994, p. 135–137, Figs. 6, 9) indicated that the lower part of the Priabona section belongs to the *Melitasphaeridium pseudorecurvatum* (Mps) Zone (with an undefined and undelimited lower boundary) which is correlative with Chrons C15 and C16 and Zones NP19–20 (= CP15b) and P16 at Massignano. This zone extends lower in the Massignano section into Zones NP18 (= CP15a) and P15 and lower Chronozone C16n, which suggested to Brinkhuis (1992) that the lowermost part of the Priabonian Stage sensu lato may not be present at Priabona if the commonly accepted correlation of the base of the Priabonian with the NP17/NP18 boundary is followed. The latter interpretation, however, is an arbitrary one in the absence of a more definitive GSSP for the base of the Priabonian (BKF85) on the basis of which a definitive biostratigraphic criterion(a) could be chosen for the purpose of regional/global correlation. Precise numerical age constraints on the base of the Priabonian are also lacking. Odin (1982, p. 786) listed an average whole rock age of 39.9 ± 1.1 Ma on pre-Priabonian lavas near the village of Priabona, suggesting a maximum age for the base of the Priabonian, and more recently Odin and Montanari (1989) have suggested an age of 37 ± 2 Ma for a stratigraphic level about 5-m above the base of the Priabona section. We follow earlier placement of the Bartonian/Priabonian boundary at the NP17/NP18 zonal boundary (BKF85; Aubry, 1986, p. 322, Fig. 16; Haq and others, 1988, p. 92, Fig. 14) which remains correlated with the younger part of Chron C17n with an estimated age of 36.9 Ma (40 Ma in BKF 85 and 39.4 Ma in Haq and others, 1988).

Eocene/Oligocene boundary.—

The position and age of the Eocene/Oligocene boundary are intimately associated with problems pertaining to the litho- and biostratigraphic characteristics and limits of the upper Eocene Priabonian and lower Oligocene “standard” stages. Since 1985, the Priabonian Stage has been the focus of considerable, and renewed, interest, and three studies, in particular, are significant in the context of this paper: Barbin (1986), Brinkhuis (1992) and Brinkhuis and Biffi (1993). At the same time, a series of studies devoted to determining a GSSP for the Eocene/Oligocene boundary (Pomerol and Premoli Silva, 1986; Premoli Silva and others, 1988b) have been published. A GSSP for the Eocene/Oligocene boundary was determined in the Massignano section of the Apennines at a level denoted by the LAD of *Hantkenina* spp. which is located in the younger part of Chron C13r (= Chron C13r (0.14); Berggren and others, 1992) with an age estimated at 33.7 Ma. More recently, however, Brinkhuis (1992) and Brinkhuis and Biffi (1993) have indicated that at Massignano the *Hantkenina* LAD occurs just below the boundary between the *Achomosphaera alcicornu* (Aal) and *Glyptrocysta semitecta* (Gse) Zones which in the section at Priabona

falls near the boundary between the Nodular Limestone and the *Asterodiscus* Beds, that is within the mid-part of the lithostratigraphic sequence assigned to the Priabonian. The top of the Priabonian Stage at Priabona (= the "Bryozoan Limestone") is assignable to the *Areosphaeridium diktyoplocus* (Adi) Zone which is correlated with the TA4.3/4.4 third-order cycle boundary of Haq and others (1988) at a level equivalent to Chron C13n. At the nearby Bressana section, this level is equivalent to the boundary between the *Areosphaeridium diktyoplocus* (Adi) and *Reticulatosphaera actinocoronata* (Rac) Zones and to the LAD of the Discocyclinidae.

Brinkhuis (1988, p. 90) makes the case for (re)defining the Eocene/Oligocene boundary in the Priabonian section(s) to correspond to the lithostratigraphic top of the Priabonian Stage which would be correlative with the TA4.3/4.4 cycle boundary and the $\delta^{18}\text{O}$ event believed to indicate a major expansion (if not initial growth) of a continental ice sheet on Antarctica. The temporal difference between these two placements of the Eocene/Oligocene boundary is on the order of 0.5 my or less. However, in stratotypifying the Eocene/Oligocene boundary in the Massignano section, the precept that "base defines unit" and that the boundaries of lower level units in the chronostratigraphic hierarchy automatically encompass the boundaries in the next higher level (on the principle of coterminous boundaries) was ignored. Instead, it will be seen that stratotypification of the Eocene/Oligocene boundary in the Massignano section automatically delimits (by decapitation) the upper level(s) of the Priabonian Stage and the lower limit of the Rupelian Stage (by temporal extension) so that they become coterminous. Realism, and a respect for the history of debate on chronostratigraphic boundaries would suggest, however, that we have not heard the last word on the subject of the Eocene/Oligocene boundary.

Lower/upper Oligocene boundary.—

We retain an informal two-fold chronostratigraphic subdivision of the Oligocene Series: a lower Rupelian and upper Chatian Stage. We correlate (as before, BKF85) the boundary between these two stages to the P21a/b boundary (=LAD of (common) chiloguembelinids) in (mid) Chron C10n with an estimated age of 28.5 Ma (=30 Ma in BKF85 and Haq and others, 1988).

Oligocene/Miocene boundary.—

The Paleogene/Neogene Working Group of the IUGS Neogene Subcommission (under the leadership of Professor Fritz Steininger) has been focusing on the definition of a GSSP for the Paleogene/Neogene boundary for over a decade. It has now decided (Steininger, 1994) to recommend that the GSSP be located at the 35-m level of the Rigorosa Formation in the Carrerosio-Lemme section of NW Italy corresponding to the base of Chron C6Cn.2n and the FAD of *Globorotalia kugleri* with an age estimate of 23.8 Ma (CK92/95 this paper; for a somewhat different point of view see Srinivasan and Kennett, 1983).

Chron C6Cn has a duration of about 0.76 my (CK92/95). By placing the boundary within the chron (rather than at either extreme), global correlation is assured (when only part of this normal subchron is present) with a relatively high degree of precision (<0.5 my) whereas if the boundary were to have been placed at either extreme the degree of precision would essen-

tially be delimited by the duration of the entire subchron (under the most unfavorable circumstance, which is frequently the case in hiatus ridden sections on both land and in the deep sea).

Neogene Period

Miocene Series.—

A three-fold subdivision of the Miocene Series is generally accepted by most stratigraphers (Berggren, 1971; BKV85). The relationship between calcareous plankton biostratigraphy and standard chronostratigraphic units was discussed at length in BKVC85 and the reader is referred to that source for background information. We review here only several (minor) adjustments and/or studies that have been made since 1985.

The Aquitanian/Burdigalian boundary in the Contessa section (Gubbio, Italy) has been correlated with the FAD of *Globigerinoides altiaperturus* (Iaccarino, 1985), and the Burdigalian/Langhian boundary with the FAD of *Pr. glomerosa* (Cita and Premoli Silva, 1968). The base of the Langhian Stage was subsequently (Cita and Blow, 1969) said to correspond to the FAD of *Pr. bisphericus* (vel *sicana*) which is stratigraphically slightly lower/older than the FAD of *Pr. glomerosa glomerosa* (Blow, 1969; Jenkins and others, 1981). We use the FAD of *Pr. sicana* (non *bisphericus*) to denote the base of the Langhian here. The Langhian/Serravallian boundary remains somewhat controversial (see discussion in BKV85 and Iaccarino, 1985). Originally defined so as to coincide with the LAD of *Pr. glomerosa* (Cita and Premoli Silva, 1968) which occurs within the interval of Zone N9 (Blow, 1969), it was subsequently defined to coincide with the N10/N11 zonal boundary of Blow (1969) in Cita and Blow (1969). Iaccarino (1985) drew attention to the fact that the upper limit of the type Langhian coincides with the top of the Cessole Formation as originally defined by Cita and Premoli Silva (1960), coincident in turn, with the top of their *Orbulina suturalis* Zone, a level which is within the upper part of Zone N9 of Blow (1969). Iaccarino (1985) accordingly equates the Langhian/Serravallian boundary with the LAD of *Pr. glomerosa* which she indicates is approximately correlative with the upper part of the *Orbulina suturalis* Zone which is correlative, in turn, with the upper part of Zone N9. Our data (see Table 11) indicates that these events occur essentially simultaneously and coincident with the FAD of *Globorotalia peripheroacuta* (=Zone N9/N10 boundary of Blow, 1969, 1979, and M6/M7 zonal boundary of this paper) and we have thus drawn the Langhian/Serravallian boundary coincident with the N9/N10 (=M6/M7) zonal boundary (Figs. 4, 5). This level would appear to be consistent with, and equivalent to, the base of the Serravallian type section as (re)defined by Vervloet (1966) and correlated with the base of his *Globorotalia menardii* (including *Globorotalia praemenardii*) Zone. The FAD of *Gt. praemenardii* coincides essentially with the base of Zone N10 (Bolli and Saunders, 1985).

The upper limit of the Serravallian Stage, as redefined by Boni (1967) and Mosna and Micheletti (1968) in the Gavi section is older than the FAD of *Gt. lenguaensis*, whereas the Arguello-Lequio parastratotype section of Cita and Premoli Silva (1968) included a *Gt. mayeri*—*Gt. lenguaensis* Zone in its upper part, indicating that the upper stratigraphic limit of the Serravallian Stage is within Zone N14 (Blow, 1969; =M11 of this paper). There is thus a short gap between the top of the Serra-

vallian and the base of the Tortonian Stage which lies within (the lower part of) Zone N15 (=M12) and perhaps upper N14 (=M11).

The lower boundary of the Messinian Stage has undergone several modifications over the past 40 years (compare Gianotti, 1953; Selli, 1960; d'Onofrio and others, 1975; Colalongo and others, 1979) with the latter study suggesting that the GSSP of the Tortonian/Messinian boundary stratotype be linked with the FAD of *Gt. conomiozea* in the Falconara section in Sicily. We follow this convention in this study.

Pliocene Series.—

The Miocene/Pliocene boundary is equated here with the base of the Zanclean Stage as stratotypified at Capo Rosello in Sicily (Cita, 1975; Hilgen, 1991; Hilgen and Langereis, 1993; Langereis and Hilgen, 1991) which appears to be bracketed by the FADs of *Gt. tumida* and *Gt. sphericomicoza* (below) and the FADs of *Ceratolithus acutus* and *Gt. puncticulata* and the LAD of *Discocaster quinqueramus* (above). An alternative point of view suggests that in view of the perimediterranean lithologic unconformity between the nonmarine Messinian (below) and marine Zanclean (above) sediments and the difficulty of biostratigraphically extending the lithostratigraphic base of the Zanclean Stage away from its stratotype area, a boundary stratotype section should be sought in a continuous marine section outside the Mediterranean (for further discussion see Berggren and others, 1995; Benson and Hodell, 1994). For the purpose of this paper, we follow the commonly accepted usage of the base of the Pliocene equals the base of the Zanclean Stage (*sensu* Cita, 1975; see also Hilgen and Langereis, 1993).

A comprehensive discussion on Pliocene and Pleistocene chronostratigraphy and chronology is presented in Berggren and others (1995).

CHRONOLOGY OF CHRONOSTRATIGRAPHY

Paleogene Period

The relationship of Paleogene epoch/series and age/stage boundaries to the revised magnetostratigraphy of CK92/95 and estimated duration (in my) of these units are shown in Figure 23. The age estimates of the older and younger boundaries of the Paleogene Period are similar to those in BKF85 (65.0 vs. 66.4 Ma and 23.8 vs 23.7 Ma, respectively; Fig. 23). The main changes relative to BKF85 involve the younger age estimates of the Eocene/Oligocene boundary (33.7 Ma) and for the Paleocene/Eocene boundary (54.8 Ma) based on new (post-1985) data, resulting in a somewhat longer Paleocene (11.6 my vs. 8.6 my in BKF85) and shorter Oligocene Epoch (9.9 vs. 12.6 my in BKF85) with the Eocene Epoch remaining essentially of the same duration. The basic reasons requiring a change in the Eocene/Oligocene boundary estimate have been reviewed by Swisher and Prothero (1990), Prothero and Swisher (1992) and Berggren and others (1992) and need not be repeated here. With regards to the Paleocene/Eocene boundary, the new ^{40}Ar - ^{39}Ar dates of 54.5 and 55 Ma on the -17 Ash Bed in NW Europe which lies virtually at the Paleocene/Eocene boundary results in a boundary estimate some 2 my younger than that estimated in BKF85 (Swisher and Knox, 1991).

Paleogene ages vary in duration by a factor of two with the Selandian (3.0 my) and the Lutetian Age (7.65 my) as the short-

EPOCH/SERIES	AGE/STAGE	DURATION IN MY	PALaeOMAGNETIC
			CALIBRATION
MIOCENE	Aquitanian		
23.8	Chattian (4.7)		C6Cn.2n _(o)
OLIGOCENE	28.5		C10n
9.9	Rupelian (5.2)		
33.7	Priabonian (3.3)		C13r.(14)
	37		C17n _(y)
	Bartonian (4.3)		
EOCENE	41.3		C19n _(y)
21.0 [21.3]	Lutetian (7.7)		
	49		C22n _(y)
	Ypresian (5.5) [5.8]		
54.5 [54.8]	Thanetian (3.4) [3.1]		C24r
	57.9		C26n
PALEOCENE	Selandian (3.0)		
10.5 [10.2]	60.90		C27n _(y)
	Danian (4.1)		
65.0	Maestrichtian		C29r
CRETACEOUS			

FIG. 23.—Chronology of Paleogene chronostratigraphy. Different ages and duration of Paleocene and Eocene and Thanetian and Ypresian ages due to estimated age of Paleocene/Eocene boundary on base of London Clay Formation at 54.5 Ma (—17 Ash date of Swisher and Knox, 1991) or 54.8 Ma (based on sedimentation rate estimates in DSDP Hole 550; Berggren and Aubry, 1995; Aubry and others, 1995). The latter age is preferred here.

est and longest, respectively (Table 5). The late Paleocene Selandian (3.0 my) and Thanetian (3.4/3.1 my) Ages are seen (Fig. 23) to have individual duration comparable to the early Paleocene Danian Age (4.1 my). The 3.4/3.1-my duration of the Thanetian Age compares with 2.8 my in BKF85, while the 7.65-my duration of the Lutetian compares with the 8.35-my duration in BKF85. The shorter Oligocene results in a shorter duration for the Rupelian (5.2 vs. 6.3 my in BKF85) and Chattian (5.2 vs. 6.3 my) Ages.

The revised Paleogene time scale presented here is seen to have elements in common with earlier, and other, versions. There appears to be general agreement among most time scale proponents of the older and younger limits of the Paleogene, although the current controversy among specialists as to the precise age of the Cretaceous/Paleogene boundary (see Obrovich, 1993, for example) remains unresolved at this time. The boundary age estimate of 65.0 Ma used here has been adopted by Gradstein and others (1994; this volume) for their newly proposed Mesozoic time scale providing continuity with our time scale. At the same time, it must be remembered that proponents of different time scales have chosen different (bio)stratigraphic levels for their boundary estimates in some instances, and these must be considered in interpreting the dif-

ferent numerical values used in different scales. For instance, the level at which the Oligocene/Miocene boundary is placed in GTS89 is slightly different than that used in BKF85 and significantly different than that in Haq and others (1988), while the level at which GTS89 place the Rupelian/Chattian boundary differs significantly from that used in BKF85 and this paper; the chronologic difference is almost 2 my! Within the Paleogene Period, we have adopted the values proposed by Montanari and others (1988; see also McIntosh and others, 1992) for the Eocene/Oligocene boundary. Other and earlier versions appear to have underestimated (by 1 to 2 my) or overestimated (by 1 to 5 my; see Berggren and others, 1992, Fig. 13) the age of this boundary, and there is now agreement on this value in the present scale and that recently published by Odin and Odin (1990).

The Paleocene/Eocene boundary is now seen to have an age of about 54.5–54.8 Ma. Earlier and other versions have hovered tantalizingly close to these values, although deviations of as much as 4 my younger (Curry and Odin, 1982) and nearly 3 my older (BKF85) have occurred in the past decade.

Age estimates of the various Paleogene stage boundaries in the various chronologies published over the past twenty years vary as a function of the ages assigned to the major epoch/series boundaries (Fig. 24) and the methodologies used to derive the time scale itself (see discussion of this problem in BKF85; Berggren, 1986; Berggren and others, 1992; Odin and Luterbacher, 1992). In general, the numerical estimates derived here are similar to those in Haq and others (1988) for the Paleocene–middle Eocene Epochs. Upper Eocene and Oligocene age estimates are unique to this time scale because of the revised age of the Eocene/Oligocene boundary, but bear similarities to those proposed in Curry and Odin (1982) and Odin and Luterbacher (1992). The main differences remaining between the geochronology presented here and that suggested by Odin and Luterbacher (1992) are at the Paleocene/Eocene boundary (~54.5–55 Ma, this paper, vs. 53 Ma in Odin and Luterbacher, 1992) and the Ypresian/Lutetian boundary (49 Ma, this paper, vs. 46 Ma in Odin and Luterbacher, 1992). It would appear that we have reached, after two decades of concentrated research on Paleogene chronology, a point where a general unity of opinion

is possible on the numerical ages of the major (epoch/series) and minor (age/stage) boundaries. We believe that future changes to the time scale presented here will involve relatively minor adjustments based on (possible) modifications to the age of the Cretaceous/Paleogene boundary, modifications to the present biostratigraphic correlation of age/stage boundaries based on boundary stratotype studies currently underway, and refinements based on the application of Milankovitch identified cyclicity to the stratigraphic record.

Neogene Period

The relationship of Neogene chronostratigraphic boundaries to the revised GPTS of this paper is shown in Figure 25. The Oligocene/Miocene boundary, as calibrated to Chron C6C.2n has an estimated age of 23.8 Ma and corresponds to the FAD of *Gt. kugleri* (BKV85; CK92/95 and this paper). The early Miocene Epoch is biostratigraphically bracketed by the FAD of *Gt. kugleri* and the FAD of *Pr. sicana* (Chron C5Cn.2n; 16.4 Ma) giving the early Miocene Epoch a duration of 7.4 my. The Aquitanian/Burdigalian boundary has been correlated with the LAD of *Gt. kugleri* (= N4/N5 boundary of Blow, 1969, 1979; M1/M2 zonal boundary of Berggren, this paper), but it has also been correlated with the FAD of *Gd. altiaperturus* in Mediterranean and Aquitaine Basin stratigraphies (see discussion in Montanari and others, 1991). The LAD of *Gt. kugleri* has been observed in Chron C6Ar (with an estimated age of 21.5 Ma) in Hole 516F, whereas it has been recorded at the base of Chron

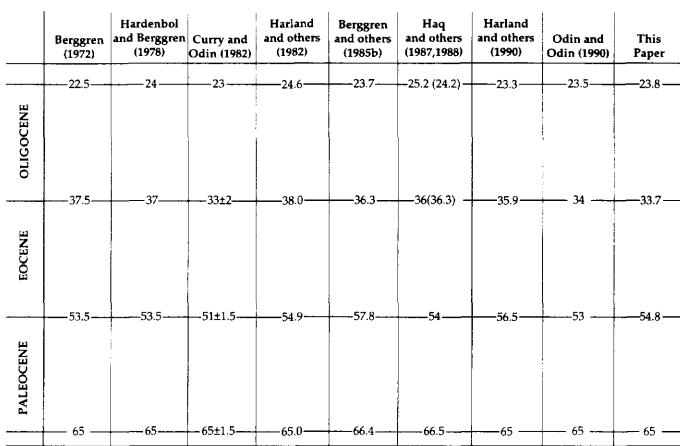


FIG. 24.—Age estimates of Paleogene epoch/series boundaries. Ages in parentheses are recalibrated to same magnetostratigraphic level as in Berggren and others (1985b).

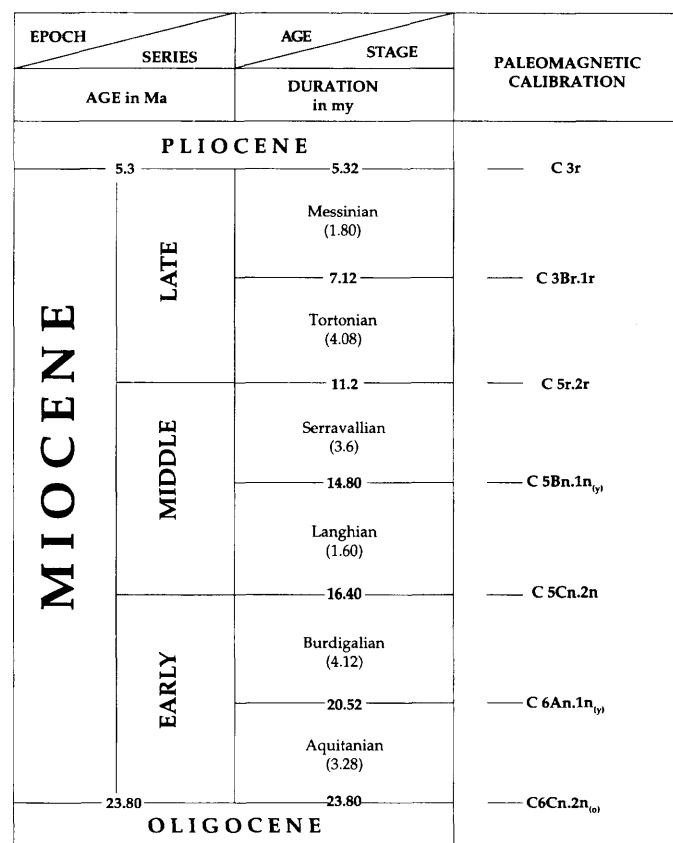


FIG. 25.—Chronology of Neogene chronostratigraphy.

C6An (with an estimated age of 21.32 Ma) in the Contessa Highway section (Montanari and others, 1990, 1991). The FAD of *Gd. altiaperturus* has been recorded at the top of Chronozone C6An (with an estimated age of 20.52 Ma (CK95) in DSDP Hole 516F, whereas it has been recorded in the older part of Chron C6r (with an estimated age that is indistinguishable from that of 20.5 Ma of the record in Hole 516F, in view of the fact that the entire Chron C6r is only 0.387 my long in the chronology of CK92/95; this paper) in the Contessa Highway section (Montanari and others, 1991). Accordingly, we would recommend correlation of the Aquitanian/Burdigalian boundary with the top of Chron C6An (with an estimated age of 20.52 Ma; CK92/95 and this paper); this procedure would facilitate regional/global correlation and would correspond with generally accepted practice in Mediterranean stratigraphies where Neogene chronostratigraphy is rooted (van Couvering and Berggren, 1977). We note, in passing, the close temporal correspondence between the estimated ages of Chron C6An in the chronologies of CK92/95 and this paper, and Montanari and others (1991). The latter have obtained an isochron age of 21.17 ± 0.23 Ma based on $^{40}\text{Ar}/^{39}\text{Ar}$ dating of plagioclase on an ash termed the Livello Rafaello, about a half meter below the LAD of *Gt. kugleri* and the base of Chron C6An. Chron C6An has an estimated age of 20.518–21.320 Ma in the magnetochronology of CK92/95. The Burdigalian/Langhian boundary (=FAD of *Pr. sicana*) is calibrated to Chron C5Cn.2n (16.4 Ma; CK92/95 and this paper).

Middle Miocene time is biostratigraphically bracketed by the FAD of *Pr. sicana* and a level within Zone M12 (i.e., between the LAD of *N. mayeri* and the FAD of *N. acostaensis* (Cita and others, 1965; cf. BKVC85 in which the middle/upper Miocene boundary was pragmatically, but incorrectly, correlated with the FAD of *N. acostaensis*). The restoration of Zone M12 (=N15; Berggren, 1993) with an estimated duration of ~0.5 my between 11.4 and 10.9 Ma (this paper) suggests that the middle/late (Serravallian/Tortonian) boundary is in Chron C5r.2r at ~11.2 Ma. The Langhian/Serravallian boundary is correlated here with the FAD of *Gt. peripheroacuta* at the top of Chron C5Bn (14.8 Ma; CK 92/95 and this paper). The middle Miocene Epoch has a time span of ~5.2 my (16.4–11.2 Ma).

The upper Miocene (Tortonian and Messinian Stages) series is bracketed biostratigraphically by a level within Zone M12 (=N15, ~11.2 Ma) to a level slightly higher/younger than the FAD of *Gt. tumida* (M14/P11 boundary) and/or *Gt. sphericomiciozea* which lies within Chron C3r with an estimated age of 5.6 Ma (this paper). The Tortonian/Messinian boundary is correlated here with the FAD of *Gt. conomiozea* which has been magnetobiostratigraphically correlated in Crete with Chron C3Br.1r with an estimated (astrochronologic) age of 7.1 Ma (Krijgsman and others, 1994). Calibration to CK92 yields an age estimate of 6.92 Ma and, in the chronology subsequently derived by CK92/95, a magnetochronologic age estimate of 7.12 Ma, essentially identical to the age estimate of Krijgsman and others (1994). A slightly younger position for the FAD of *conomiozea* in Chron C3Bn has been reported by Benson and Rakic-El Bied (1991) in the Vera Basin of Spain which would place this event at ~7.0 Ma in the chronology adopted here. Thus, the astrochronologic and magnetochronologic scales are seen to be coherent and concordant back to Chron C3Br at ~7 Ma. At the same time, we note that the late Miocene (Chron 6)

carbon shift has been observed to start near the base of Chron 6 in Hole 588 (Hodell and Kennett, 1986) equal Chron C3Br.2r (7.20 Ma in CK92; 7.4 Ma in CK92/95 and this paper). An age of 7.26 ± 0.1 Ma for the Tortonian/Messinian boundary in the northern Apennines of Romagna was recently suggested by Vai and others (1993) based on a K-Ar (biotite) and a $^{40}\text{Ar}/^{39}\text{Ar}$ (plagioclase) date of 7.33 Ma on volcanic horizons a few meters below the FAD of *Gt. conomiozea* and *Gt. mediterranea* and a K-Ar (biotite) date of 7.72 ± 0.15 Ma on the stratigraphically lower FAD of *Globorotalia suterae* (which agrees closely with the magnetochronologic estimate of 7.12 Ma for this datum event proposed here; Table 11; cf. the estimate of 5.6 Ma and correlation to Chron C3An for the Tortonian/Messinian boundary by Langereis and Dekkers, 1992). The late Miocene Epoch thus has a span of ~6 my (11.2–5.3 Ma). In a recent integrated magnetobiostratigraphic study of the Sorbas (Andalusia, Spain) and Caltanissetta (Sicily, Italy) Basins, the evaporitic phase (“salinity crisis”) of the Mediterranean has been shown to be restricted to Chron C3r (Gilbert reversed) and to have had a duration of <0.5 my (from ~5.8–5.32 Ma in the chronology of this paper; Gaultier and others, 1994). The implication of these results is that the pre-evaporitic Messinian (~7.12 to ~5.8 Ma (~1.32 my) represents about 2/3 of the duration of the Messinian Age itself (7.12–5.32 Ma, or ~1.80 my), whereas the “late” (evaporitic) Messinian represents but 1/3 the duration of the Messinian Age (~5.8–5.32 Ma, or ~0.48 my). Comparable studies on a Moroccan drill hole have yielded a high-resolution integrated magnetobiostratigraphic and stable isotope stratigraphy of correlative upper Miocene non-evaporitic (Atlantic facies) strata (Hodell and others, 1994).

There is ongoing debate regarding the adoption of an astronomically calibrated (Hilgen and Langereis, 1989) versus anomaly interpolated (Cande and Kent, 1992) based time scale for the Neogene Period, but this is beyond the scope of this paper. At the present time, the Cande and Kent (1995) modification adopts directly the astronomical time scale to the Thvera Event (Subchron C3n.4n) which results in good concordance of the time scales back to about 7 Ma (see above). The situation is discussed at length in Berggren and others (1995) to which the reader is referred.

Postscript.—Following the completion and submission of this paper, our attention has been drawn to the paper by Wei (1995) which questions the validity of several of the calibration points of the geomagnetic polarity time scale of Cande and Kent (1992, 1995). Space does not allow a detailed discussion of this work but we comment on several points of concern relative to the time scale published here.

1. For the early middle Miocene calibration, Wei (1995, p. 957) substitutes an age of 16.3 Ma for Chron C5Br(y) based on the “clear correlation of the magnetic reversal sequence of the Columbia River Basalt with seafloor anomaly pattern (Baksi and Farrar, 1990).” The interpretation of this magnetic reversal sequence is anything but unambiguous, as we have discussed above, especially when contradictory evidence from the Barstow Formation (Wyoming) and the Ngorora Formation (Kenya) are considered. In the construction of our time scale, we have assiduously avoided the use of nonmarine calibration(s) because of lack of independent (i.e., marine biostratigraphic) constraints (cf. BKVF85).

Thus we used an estimate of 14.8 Ma for the N9/N10 zonal boundary based on an assessment of radioisotopic dates near the *Orbulina* Datum in Japan (Tsuchi and others, 1981; Shibata and others, 1984; Tsuchi, 1984) and, particularly, in Martinique (Andreieff, 1985; Andreieff, person. commun. to WAB, 1985) which were correlated albeit indirectly to the geomagnetic polarity time scale as the best available calibration for early middle Miocene time. We take this opportunity of clarifying several points regarding our choice of the 14.8 Ma calibration point at the N9/N10 zonal boundary

- a. At Le François, Martinique, sediments with a *Globorotalia peripheroronta* (N9) Zone fauna are overlain by basalts of the Vert-Pré volcanic episode dated at 15.1 ± 0.3 Ma (Pacquemar Quarry).
- b. At Bassignac, Martinique, the "Tufs de Bassignac" belonging to the same Zone N9 are directly underlain by andesites of the François-Robert volcanic episode dated at 15.9 ± 1 Ma (Bois-soldat Quarry) and 15.69 ± 1 Ma (Ilet à Bau, Le Robert Bay).
- c. At Le Marin, Martinique, sediments assigned to the early *Globorotalia fohsi* (N10) Biochron are underlain by the Vert-Pré volcanics (15.1 ± 0.3 Ma, cf. supra).

Andreieff subsequently suggested in a written communication to WAB (1985) that the best estimate for the N9/N10 zonal boundary was 14.8 Ma, the value we adopted in BKFV85 and which was accepted in CK92, 95. The work by Andreieff (1985) was an internal report prepared for the Bureau de Recherches Géologiques et Minières as part of the "Explanatory Notes" to accompany the new geological map of Martinique (scale 1:50,000) which was eventually published in 1989. The information reviewed above was published in more detail as Andreieff and others (1988).

The use of a 16.3 Ma calibration for Chron C5Br(y) by Wei results in age estimates ~ 1 my older than those in CK95 but are contradicted by a large body of integrated magnetobiostratigraphic and radioisotopic data in the early-middle Miocene, not the least of which are several dates of ~ 15 Ma near the *Orbulina* datum (Chron C5Bn.2n) and ~ 16 Ma near the *Praeorbula glomerosa* Datum (early Biochron N8 = Chron C5Cn.1n; Tsuchi and others, 1981; Shibata and others, 1984; Andreieff, 1985; Andreieff and others, 1988), ~ 1 my younger than inferred by Wei (1995).

2. As pointed out by Wei (1995), Bryan and Duncan (1983) reported dates of 45.8 Ma and 46.8 Ma on duplicate samples of biotite from a clastic horizon in DSDP Hole 516F considered to lie in the younger part of C21n (Berggren and others, 1983). In a review of Paleogene geochronology by Berggren and others (1992), the 45.8 Ma date was inadvertently omitted in a tabulation of Eocene-Oligocene radioisotopic ages and magnetobiostratigraphic controls. This omission was propagated in CK92/95 who used the 46.8 Ma date as a calibration point for the middle Eocene (Chron C21n(0.33)). The mean in the Hole 516F biotite ages, given as 46.3 ± 0.7 Ma by Bryan and Duncan (1983), in conjunction with the dates of 45.7 Ma and 46.2 Ma on bentonite from the lower Castle Hayne Formation (Harris and Fullager, 1989) which is biostratigraphically constrained to the older part of Chron C20r (Berggren and others, 1992) would

nevertheless suggest an age of ~ 46 Ma for the Chron C20r/C21n boundary, not very different from 46.264 Ma derived in CK95 and used here. $^{40}\text{Ar}/^{39}\text{Ar}$ laser total-fusion analyses of sanidine and biotite from the clastic horizon in Hole 516F (Swisher and Montanari, in prep.) now appear to provide dates of ~ 45.6 Ma that are concordant with the younger biotite date (45.8 Ma) reported by Bryan and Duncan (1983). Thus, Wei's remark (1995) that the isotopic age on the biotite from Hole 516F may have been unsuitable as a calibration point due to the large age uncertainty is well taken. The isotopic dates by Swisher and Montanari (in prep.) however, became available after CK95 was in press and at a late stage in the preparation of this time scale. On the other hand, Wei (1995) did not use a middle Eocene calibration point, which results in a rather long (17.6 my) gap between calibration points in the early and late Eocene.

Wei (1995) also casts doubt on the reliability of the 46.8 Ma calibration point in CK92/95 based on the fact that the biotite bearing clastic levels in Hole 516F are turbidite horizons and that their position in Chron C21n is uncertain because of the presence of a slump block below the normal polarity interval assigned to Chron C21n in the hole. The turbiditic nature of the biotic-bearing horizons is of minor concern in as much as (1) they are considered "locally derived from a mixed volcanic/plutonic terrain . . . , alkaline volcanoes active on the Rio Grand Rise in the middle Eocene" being "the most probable source for this ash" (= "the [dated] biotite separated from Sample 516F-76-4, 107–115 cm") (Bryan and Ducan, 1983, p. 475); and (2) they occur in sediments assigned to Zone NP15 by Wei and Wise (1989). From the range of the calcareous nannofossil species recorded by these authors, it is unquestionable that the normal polarity interval in Core 516F-76-5 to 75-1, correlative with the lower part of Zone NP15, represents Chron C21n. However, of greater concern to us than the presence of a Maestrichtian slump in Core 516F-78 and 79 (*partim*) is the fact that the normal polarity interval interpreted as Chron C21n in Berggren and others (1983) corresponds in fact to the concatenation of two normal magnetozones, one of which corresponds to the late part of Chron C21n in the other to Chron C22n (Aubry, this volume). Yet, using the high sedimentation rates calculated by Aubry, it is serendipitously likely that the dated biotite in Hole 516F lies at a young level in Chron C21n (0.33 or less). In view of the rapidly changing dating scenario of Chron C21n, we chose to retain the calibration value of 46.8 Ma in CK95 for this paper rather than generate yet another permutation in the Cenozoic time scale until a stable solution is achieved.

3. Wei (1995) substitutes an age calibration of 52.8 Ma at Chron C24n.1r(y) from the nonmarine Willwood Formation in Wyoming (Tauxe and others, 1994; Wing and others, 1991) for the 55 Ma age estimate of CK95 at the NP9/NP10 zonal boundary in Chron C24r. There are several points here:
 - a. Wei (1995) states that the 55 Ma at the NP9/NP10 zonal boundary was based on "the $^{40}\text{Ar}/^{39}\text{Ar}$ date of 54.5 Ma for the -17 Ash by Swisher and Knox (1991), who estimated an age of 55 Ma for the nannofossil NP9/NP10 boundary (~Paleocene/Eocene boundary) based on the short distance from the -17 Ash to the NP9/NP10 boundary in DSDP Hole 550". Actually, Swisher and Knox

(1991) based their age of 55 Ma on the NP9/NP10 zonal boundary on sedimentation-rate extrapolation over the 7-m interval separating the -17 Ash and the NP9/NP10 zonal boundary based on Swisher's ages of 54.0 Ma and 54.5 Ma on the +19 and -17 Ash beds, respectively, themselves separated by 7 m. Parenthetically, there are two sets of ages on these two ashes, one by Carl Swisher and the other by John Obradovich (abbreviated here to CCS and JDO, respectively). The ages are:

- +19 Ash: 54.0 Ma (CCS) and 54.5 Ma (JDO)
- 17 Ash: 54.5 Ma (CCS) and 55.0 Ma (JDO)

The ages on the +19 Ash have been disavowed by both workers (pers. communs. to WAB, 1994) owing to inhomogeneities in the mineral populations. Nonetheless, radioisotopic dating of the -17 Ash indicates an age of 54.5 to 55 Ma for the Paleocene/Eocene boundary, as denoted at the base of the Ieper Clay in Belgium and/or the base of the London Clay Formation (Oldhaven/Hales Clay Beds) in the London—Hampshire Basin.

- b. Wei (1995) states that the NP9/NP10 zonal boundary lies at an unconformity at 408 m in DSDP Hole 550, resulting in an uncertain position of CK95's tie point within Chron C24r. Although we agree with the presence of an unconformity, we view the evidence that he cites as supportive (juxtaposed disappearance of *Fasciculithus tympaniformis* and appearances of *Discoaster diastypus* and *Coccolithus formosus* at a lithologic boundary) inadequate for this assertion. We also point out that the presence of an unconformity at 408 m in Hole 550 does not necessarily jeopardize the validity of the NP9/NP10 tie point.
- c. Subsequent to CK92, a hiatus at 408 m in DSDP Hole 550 has been determined based on integrated magneto-, bio-, and isotope stratigraphy (Aubry and others, 1995) and its implication for geochronology has been discussed in detail (Aubry and others, 1995; Berggren and Aubry, 1995). It has been shown that the hiatus is substantive (~0.3 to 0.5 my) and encompasses the later part of Biochron NP9 and the earlier part of Biochron NP10. It is now clear that the position of the NP9/NP10 biochronal boundary in Chron C24r is younger than accepted in CK95, but the ages of Subchron C24n estimated in CK95 are nevertheless internally consistent and acceptable. Indeed, the calibration age of 52.8 Ma at the Chron C24n.1r(y) used by Wei (1995) differs insignificantly from the value (52.663 Ma) for this reversal in CK95.
4. With regard to the other calibrations proposed by Wei (1995), 9.67 Ma for Chron C5n(y) differs by only 0.07 my from the estimate of 9.740 Ma derived in CK95, 28.1 Ma for Chron C9r(y) differs by <0.15 my from the estimate of 27.972 Ma, and 35.2 Ma for Chron C15r(y) differs by <0.3 my from the estimate of 34.940 Ma. Indeed as Wei (1995) observes, with the exception of the early Miocene where the differences are up to 1.3 my due to what we regard as the ambiguous Columbia River Basalt tie point, the differences over the Cenozoic are generally less than 0.3 my. The revised calibration of Wei (1995) scarcely offers a significant improvement to the GPTS of CK95 and that presented here and indeed, supports its robustness.

With the increasing generation of high precision radioisotopic dates, we anticipate that the next significant advance

in age calibrations will include more precise methods (e.g., astronomical climate cycles) to relate the dated level(s) in stratigraphic sections to the isochronous boundaries (e.g., magnetochrons) that are used for global correlations.

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REFERENCES

- ALI, J. R., KING, C., AND HAILWOOD, E., 1993, Magnetostratigraphic calibration of early Eocene depositional sequences in the southern North Sea Basin, in Hailwood, E. A. and Kidd, R. B., eds., High Resolution Stratigraphy: London, Geological Society Special Publication 70, p. 99–125.
- ALIMARINA, V. P., 1962, Observations on the evolution of planktonic foraminifera in the early Paleogene of the northern Caucasus: Biulletin Moskovsk Obschchii ispytatelei prirody, otdel geologii, v. 37, p. 128–129 (in Russian).
- ALIMARINA, V. P., 1963, Some peculiarities in the development of planktonic foraminifera and zonation of the Lower Paleogene of the northern Caucasus: Voprosy Mikropaleontologii, v. 7, p. 158–195 (in Russian).
- ALVAREZ, W., ARTHUR, M. A., FISCHER, A. G., LOWRIE, W., NAPOLEONE, G., PREMOLI SILVA, I., AND ROGGENTHEN, W. M., 1977, Upper Cretaceous-Paleocene magnetic stratigraphy at Gubbio, Italy. V. Type section for the Late Cretaceous-Paleocene geomagnetic reversal time scale: Geological Society of America Bulletin, v. 88, p. 383–389.
- ANDREIEFF, P., 1985, Biostratigraphie, chronométrie et géochronologie des formations sédimentaires anté-Quaternaires de la Martinique: Bureau de Recherches Géologiques et Minières, 18 p. (unpublished internal report).
- ANDREIEFF, P., BAUDRON, J. C., AND WESTERCAMP, D., 1988, Histoire géologique de la Martinique (Petites Antilles): Biostratigraphie (foraminifères), radiochronologie (potassium-argon), évolution volcano-structurale: Géologie de la France, no. 2–3, p. 39–70.
- ANDREIEFF, P., BELLON, H., AND WESTERCAMP, D., 1976, Chronométrie et stratigraphie comparée des édifices volcaniques et formations sédimentaires de la Martinique (Antilles françaises): Bulletin du Bureau de Recherche Géologiques et Minières, 2^e série, section 4, n° 4, p. 335–346.
- ARNOLD, A. J., 1983, Phyletic evolution in the *Globorotalia crassaformis* (Gallopaw and Wissler) lineage: a preliminary report: Paleobiology, v. 9, p. 390–397.
- AUBRY, M.-P., 1983, Biostratigraphie du Paléogène épicontinentale de l'Europe du Nord-Ouest. Etude fondée sur les nannofossiles calcaires: Documents des Laboratoires de Géologie de Lyon, v. 89, 317 p.

- AUBRY, M.-P., 1986, Paleogene calcareous nannoplankton biostratigraphy of northwestern Europe: *Palaeogeography, Paleoclimatology, Palaeoecology*, v. 55, p. 267–334.
- AUBRY, M.-P., 1991, Sequence stratigraphy: Eustasy or tectonic imprint?: *Journal of Geophysical Research*, v. 96, p. 6641–6679.
- AUBRY, M.-P., 1992a, Late Paleogene calcareous nannoplankton evolution: A tale of climatic deterioration, in Prothero, D. R. and Berggren, W. A., eds., *Eocene-Oligocene Climatic and Biotic Evolution*: Princeton, Princeton University Press, p. 272–309.
- AUBRY, M.-P., 1992b, Paleogene calcareous nannofossils from the Kerguelen Plateau, Leg 120: College Station, *Proceedings of the Ocean Drilling Program, Scientific Results*, v. 120, p. 471–491.
- AUBRY, M.-P., 1993a, Calcareous nannofossil stratigraphy of the Neogene formations of eastern Jamaica, in Robinson, E. R. and Wright, R. M., eds., *Biostratigraphy of Jamaica*: Boulder, Geological Society of America Memoir 182, p. 131–178.
- AUBRY, M.-P., 1993b, Neogene allostratigraphy and depositional history of the DeSoto Canyon area, northern Gulf of Mexico: *Micropaleontology*, v. 39, p. 327–366.
- AUBRY, M.-P., BERGGREN, W. A., KENT, D. V., FLYNN, J. J., KLITGORD, K., OBRADOVICH, J. D., AND PROTHERO, D. R., 1988, Paleogene geochronology: an integrated approach: *Paleoceanography*, v. 3, p. 707–742.
- AUBRY, M.-P., BERGGREN, W. A., STOTT, L. D., AND SINHA, A., 1995, The upper Paleocene-lower Eocene stratigraphic record and the Paleocene/Eocene boundary isotope excursion: implications for geochemistry, in Knox, R. O'B., Corfield, R. M., and Dunnay, R. E., eds., *Correlation of the Early Paleogene in Northwestern Europe*: London, Special Publication of the Geological Society (in press).
- AUBRY, M.-P., HAILWOOD, E., AND TOWNSEND, H., 1986, Magneto- and calcareous nannofossil stratigraphy of the lower Paleogene of the Hampshire-London Basin: *Journal of the Geological Society of London*, v. 143, p. 729–735.
- BACKMAN, J., 1987, Quantitative calcareous nannofossil biochronology of middle Eocene through early Oligocene sediment from DSDP Sites 522 and 523: *Abhandlungen der Geologische Bundesanstalt*, v. 39, p. 21–31.
- BACKMAN, J. AND HERMELIN, J. O. R., 1986, Morphometry of the Eocene nannofossil *Reticulofenestra umbilicus* lineage and its biochronological consequences: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 57, p. 103–106.
- BACKMAN, J., SCHNEIDER, D. A., RIO, D., AND OKADA, H., 1990, Neogene low-latitude magnetostratigraphy from Site 710 and revised age estimates of Miocene nannofossil datum events: College Station, *Proceedings of Ocean Drilling Program, Scientific Results*, v. 115, p. 271–276.
- BACKMAN, J., AND SHACKLETON, N., 1983, Quantitative biochronology of Pliocene and early Pleistocene calcareous nannofossils from the Atlantic, Indian and Pacific Oceans: *Marine Micropaleontology*, v. 8, p. 141–170.
- BAKSI, A. K. 1993, A Geomagnetic Polarity Time Scale for the period 0–17 Ma, based on $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages for selected field reversals: *Geophysical Research Letters*, v. 20, p. 1607–1610.
- BAKSI, A. K. AND FARRAR, E., 1990, Evidence for errors in the Geomagnetic Polarity Time Scale at 17 to 15 Ma: $^{40}\text{Ar}/^{39}\text{Ar}$ dating of basalts from the Pacific Northwest, USA: *Geophysical Research Letters*, v. 17, p. 1117–1120.
- BAKSI, A. K., HOFFMAN, K. A., AND FARRAR, E., 1993a, A new calibration point for the late Miocene section of the Geomagnetic Polarity Time Scale: $^{40}\text{Ar}/^{39}\text{Ar}$ dating of lava flows from Akaroa Volcano, New Zealand: *Geophysical Research Letters*, v. 20, p. 667–670.
- BAKSI, A. K., HOFFMAN, K. A., AND McWILLIAMS, M., 1993b, Testing the accuracy of the geomagnetic polarity time-scale (GPTS) at 2.5 Ma, utilizing $^{40}\text{Ar}/^{39}\text{Ar}$ incremental heating data on whole-rock basalts: *Earth and Planetary Science Letters*, v. 118, p. 135–144.
- BAKSI, A. K., HSU, V., McWILLIAMS, M. O., AND FARRAR, E., 1992, $^{40}\text{Ar}/^{39}\text{Ar}$ dating of the Brunhes-Matuyama geomagnetic field reversal: *Science*, v. 256, p. 356–357.
- BAKSI, A. K., YORK, D., AND WATKINS, N. D., 1967, The age of the Steens Mountain geomagnetic polarity transition: *Journal of Geophysical Research*, v. 22, p. 6299–6308.
- BALDAUF, J. G. AND BARRON, J. A., 1991, Diatom biostratigraphy: Kerguelen Plateau and Prydz Bay regions of the southern ocean: College Station, *Proceedings of the Ocean Drilling Program, Scientific Results*, v. 119, p. 547–598.
- BANNER, F. T. AND BLOW, W. H., 1965, Progress in the planktonic foraminiferal biostratigraphy of the Neogene: *Nature*, v. 208, p. 1164–1166.
- BARBIN, V., 1986, Le Priabonian dans sa région-type (Vicentin, Italie du Nord). Stratigraphie; Micropaléontologie: *Essai d'intégration dans l'échelle chronostratigraphique*: Unpublished Ph.D. Dissertation, University Pierre et Marie Curie, Paris, 227 p.
- BARKER, P. F., JOHNSON, D., AND OTHERS, 1983, Site 516: Initial Reports of the Deep Sea Drilling Project, v. 72, p. 155–338.
- BARKER, P. F., KENNEDY, J. P., AND OTHERS, 1988, Site 689: Proceedings of the Ocean Drilling Program, Initial Reports, v. 113, p. 89–181.
- BARRON, J. A., 1985, Late Eocene to Holocene diatom biostratigraphy of the equatorial Pacific Ocean, Deep Sea Drilling Project Leg 85: College Station, *Initial Reports of the Deep Sea Drilling Project*, v. 85, p. 413–456.
- BENSON, R. H., AND HODELL, D.A., 1994, Comment on "A critical re-evaluation of the Miocene/Pliocene boundary as defined in the Mediterranean" by F. G. Hilgen and C. C. Langereis: *Earth and Planetary Science Letters*, v. 124, p. 245–250.
- BENSON, R., AND RAKIC EL BIED, K., 1991, The Messinian parastratotype at Cuevas del Almanzora, Vera Basin, SE Spain: refutation of the deep-basin, shallow-water hypothesis?: *Micropaleontology*, v. 37, p. 289–402.
- BERGGREN, W. A., 1969, Rates of evolution of some Cenozoic planktonic foraminifera: *Micropaleontology*, v. 15, p. 351–365.
- BERGGREN, W. A., 1971, Tertiary boundaries, in Funnell, B. F. and Riedel, W. R., eds., *The Micropalaeontology of the Oceans*: Cambridge, Cambridge University Press, p. 693–808.
- BERGGREN, W. A., 1972, A Cenozoic time scale—some implications for regional geology and paleobiogeography: *Lethaia*, v. 5, p. 195–215.
- BERGGREN, W. A., 1973, The Pliocene time scale: calibration of planktonic foraminifera and calcareous nannoplankton zones: *Nature*, v. 243, p. 391–397.
- BERGGREN, W. A., 1977a, Late Neogene planktonic foraminiferal biostratigraphy of the Rio Grande Rise (South Atlantic): *Marine Micropaleontology*, v. 2, p. 265–313.
- BERGGREN, W. A., 1977b, Late Neogene planktonic foraminiferal biostratigraphy of DSDP Site 357 (Rio Grande Rise): Washington, D. C., *Initial Reports of the Deep Sea Drilling Project*, v. 29, p. 591–614.
- BERGGREN, W. A., 1986, Geochronology of the Eocene/Oligocene, in Pomerol, C. and Premoli Silva, I., *Terminal Eocene Events*: Amsterdam, Elsevier, Developments in Stratigraphy 9, p. 349–356.
- BERGGREN, W. A., 1992, Neogene planktonic foraminifer magnetobiostratigraphy of the southern Kerguelen Plateau (Sites 747, 748 and 751): College Station, *Proceedings of the Ocean Drilling Program, Scientific Results*, v. 120, p. 631–647.
- BERGGREN, W. A., 1993, Neogene planktonic foraminiferal biostratigraphy of eastern Jamaica, in Wright, R. M. and Robinson, eds., *Biostratigraphy of Jamaica*: Boulder, Geological Society of America Memoir 182, p. 179–217.
- BERGGREN, W. A., 1994, In defense of the Selandian Age/Stage: *Geologiska Foreningen Forhandlingar* (Stockholm), v. 116, p. 6–8.
- BERGGREN, W. A., AND AUBRY, M.-P., 1995, A late Paleocene-early Eocene NW European and North Sea magnetobiochronologic correlation network: A sequence stratigraphic network, in Knox, R. O'B., Corfield, R. M., and Dunnay, R. E., eds., *Correlation of the Early Paleogene in Northwestern Europe*: London, Special Publication of the Geological Society (in press).
- BERGGREN, W. A., AUBRY, M.-P., AND HAMILTON, N., 1983a, Neogene magnetobiostratigraphy of DSDP Site 516 (Rio Grande Rise, South Atlantic): Washington, D.C., *Initial Reports of the Deep Sea Drilling Project*, v. 72, p. 675–706.
- BERGGREN, W. A., HAMILTON, N., JOHNSON, D. A., PUJOL, C., WEISS, W., CEPEK, P., AND GOMBOS, JR., A. M., 1983b, Magnetobiostratigraphy of Deep Sea Drilling Leg 72, Sites 515–518, Rio Grande Rise (South Atlantic): Washington, D.C., *Initial Reports of the Deep Sea Drilling Project*, v. 72, p. 939–948.
- BERGGREN, W. A., HILGEN, F. J., LANGEREIS, C. G., KENT, D. V., OBRADOVICH, J. D., RAFFI, I., RAYMO, M., AND SHACKLETON, N. J., 1995, Late Neogene (Pliocene-Pleistocene) chronology: New perspectives in high resolution stratigraphy: *Geological Society of America Bulletin*, v. 107, p. 1272–1287.
- BERGGREN, W. A., KENT, D. V., AND COUVERING, J. A., VAN, 1985a, Neogene geochronology and chronostratigraphy, in Snelling, N. J., ed., *The Chronology of the Geological Record*: London, Geological Society of London Memoir 10, p. 211–260.
- BERGGREN, W. A., KENT, D. V. AND FLYNN, J. J., 1985b, Paleogene geochronology and chronostratigraphy, in Snelling, N. J., ed., *The Chronology of the Geological Record*: London, Geological Society of London Memoir 10, p. 141–195.
- BERGGREN, W. A., KENT, D. V., FLYNN, J. J., AND COUVERING, J. A., van, 1985c, Cenozoic geochronology: *Geological Society of America Bulletin*, v. 96, p. 1407–1418.

- BERGGREN, W. A., KENT, D. V., OBRADOVICH, J. D., AND SWISHER, C. C., III, 1992, Towards a revised Paleogene geochronology, in Prothero, D. R. and Berggren, W. A., eds., Eocene-Oligocene Climatic and Biotic Evolution: Princeton, Princeton University Press, p. 29-45.
- BERGGREN, W. A. AND MILLER, K. G., 1988, Paleogene tropical planktonic foraminiferal biostratigraphy and magnetostratigraphy: *Micropaleontology*, v. 34, p. 362-380.
- BERGGREN, W. A. AND NORRIS, R. D., 1993, Origin of the genus *Acarinina* and revision to Paleocene biostratigraphy: Geological Society of America, Annual Meeting, Abstract with Programs, v. 25, p. A359.
- BERGGREN, W. A., NORRIS, R. D., AUBRY, M.-P. AND VAN FOSSEN, M., 1994, A Paleocene magnetic, biochronologic and isotopic reference section at DSDP Site 384: EOS, Transactions, American Geophysical Union, Spring Meeting, v. 75, no. 16, p. 52.
- BLAKELY, R. J., 1974, Geomagnetic reversals and crustal spreading rates during the Miocene: *Journal of Geophysical Research*, v. 79, p. 2979-2985.
- BLEIL, U., 1985, The magnetostratigraphy of northwest Pacific sediments, Deep Sea Drilling Project Leg 86: Washington, D.C., Initial Results of the Deep Sea Drilling Project, v. 86, p. 441-458.
- BLOW, W. H., 1969, Late Middle Eocene to Recent planktonic foraminiferal biostratigraphy, in Brönnimann, P. and Renz, H. H., eds., Proceedings of the First International Conference on Planktonic Microfossils (Geneva, 1967): Leiden, E. J. Brill, v. 1, p. 199-421.
- BLOW, W. H., 1979, The Cenozoic Globigerinida: A Study of the Morphology, Taxonomy, Evolutionary Relationships and the Stratigraphical Distribution of some Globigerinida (mainly Globigerinacea), 3 vols: Leiden, E. J. Brill, 1413 p.
- BLOW, W. H. AND BANNER, F., 1966, The morphology, taxonomy and biostratigraphy of *Globorotalia barisanensis* LeRoy, *Globorotalia fohsi* Cushman and Ellisor, and related taxa: *Micropaleontology*, v. 12, p. 286-303.
- BOERSMA, A., 1984, Cretaceous-Tertiary planktonic foraminifers from the southeastern Atlantic, Walvis Ridge Area, Deep Sea Drilling Project Leg 74: Washington, D.C., Initial Reports of the Deep Sea Drilling Project, v. 74, p. 501-523.
- BOLLI, H. M., 1957a, The genera *Globigerina* and *Globorotalia* in the Paleocene-lower Eocene Lizard Springs Formation of Trinidad, B.W.I.: United States National Museum Bulletin 215, p. 51-81.
- BOLLI, H. M., 1957b, Planktonic foraminifera from the Oligocene-Miocene Cipero and Lengua Formations of Trinidad, B.W.I.: United States National Museum Bulletin 215, p. 97-123.
- BOLLI, H. M., 1957c, Planktonic foraminifera from the Eocene Navet and San Fernando Formtions of Trinidad, B.W.I.: United States National Museum Bulletin 215, p. 155-172.
- BOLLI, H. M., 1966, Zonation of Cretaceous to Pliocene marine sediments based on planktonic foraminifera: Boletín Informativo, Asociacion Venezolano de Geología, Mineraria y Petroleo, v. 9, p. 3-32.
- BOLLI, H. M., 1970, The foraminifera of Sites 23-31, Leg 4: Washington D.C., Initial Results of the Deep Sea Drilling Project, v. 4, p. 577-643.
- BOLLI, H. M., 1972, The genus *Globigerinathea* Brönnimann: *Journal of Foraminiferal Resarch*, v. 2, p. 109-136.
- BOLLI, H. M. AND BERMUDEZ, P. J., 1965, Zonation based on planktonic foraminifera of Middle Miocene to Pliocene warm-water sediments: Boletín Informativo, Asociacion Venezolana di geología, Minería y Petroleo, v. 8, p. 119-149.
- BOLLI, H. M. AND KRASHENINNIKOV, V. A., 1978, Problems in Paleogene and Neogene correlations based on planktonic foraminifera: *Micropaleontology*, v. 23, p. 436-452.
- BOLLI, H. M. AND PREMOLI SILVA, I., 1973, Oligocene to Recent planktonic foraminifera and stratigraphy of the Leg 15 Sites in the Caribbean Sea: Washington, D.C., Initial Reports of the Deep Sea Drilling Project, v. 15, p. 475-497.
- BOLLI, H. M. AND SAUNDERS, J. B., 1985, Oligocene to Holocene low latitude planktic foraminifera, in Bolli, H. M., Saunders, J. B., and Perch-Nilsen, K., eds., Plankton Stratigraphy: Cambridge, Cambridge University Press, p. 155-262.
- BONI, A., 1967, Notizie sul Serravalliano tipo, in Selli, R., ed., Guida alle escursioni del IV Congresso: Committee on Mediterranean Neogene Stratigraphy, International Union of Geological Sciences, 4th International Congress, p. 47-63.
- BRINKHUIS, H., 1988, Late Eocene to early Oligocene dinoflagellate cysts from the Priabonian type-area (northeast Italy): biostratigraphy and paleoenvironmental interpretation: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 107, p. 121-163.
- BRINKHUIS, H., 1992, Late Eocene to Early Oligocene Dinoflagellate Cysts from Central and Northeast Italy: Doctoral Dissertation, University of Utrecht, 169 p. (Published privately by the author).
- BRINKHUIS, H. AND BIFFI, U., 1993, Dinoflagellate cyst stratigraphy of the Eocene/Oligocene transition in central Italy: *Marine Micropaleontology*, v. 22, p. 131-183.
- BRÖNNIMANN, P. AND RESIG, J., 1971, A Neogene globigerinacean biochronologic time-scale of the southwestern Pacific: Washington, D.C., Initial Reports of the Deep Sea Drilling Project, v. 7, p. 1235-1469.
- BRYAN, W. B. AND DUNCAN, R. A., 1983, Age and provenance of clastic horizons from Hole 516F: Washington, D.C., Initial Reports of the Deep Sea Drilling Project, v. 72, p. 475-477.
- BUKRY, D., 1973, Low-latitude coccolith biostratigraphic zonation: Washington, D.C., Initial Reports of the Deep Sea Drilling Project, v. 15, p. 127-149.
- BUKRY, D., 1975, Coccolith and silicoflagellate stratigraphy, northwestern Pacific Ocean, Deep Sea Drilling Project Leg 32: Washington D.C., Initial reports of the Deep Sea Drilling Project, v. 32, p. 677-701.
- CANDE, S. C. AND KENT, D. V., 1992, A new geomagnetic polarity time scale for the Late Cretaceous and Cenozoic: *Journal of Geophysical Research*, v. 97, p. 13,917-13,951.
- CANDE, S. C. AND KENT, D. V., 1995, Revised calibration of the geomagnetic polarity time scale for the Late Cretaceous and Cenozoic: *Journal of Geophysical Research*, v. 100, p. 6093-6095.
- CANDE, S. C. AND KRISTOFFERSEN, Y., 1977, Late Cretaceous magnetic anomalies in the North Atlantic: *Earth and Planetary Science Letters*, v. 35, p. 215-224.
- CANDE, S., LABRECQUE, J. L., AND HAXBY, W. F., 1988, Plate kinematics of the South Atlantic: Chron C34 to present: *Journal of Geophysical Research*, v. 93, p. 13,479-13,492.
- CANUDO, J. I. AND MOLINA, E., 1992, Planktic foraminiferal faunal turnover and bio-chronostratigraphy of the Paleocene-Eocene boundary at Zumaya, northern Spain: *Revista Societa Geología Espana*, v. 5, p. 145-157.
- CARO, Y., LUTERBACHER, H. P., PERCH-NIELSEN, K., PREMOLI SILVA, I., RIEDEL, W. R., AND SANFILIPPO, A., 1975, Zonations à l'aide de microfossiles pélagiques du Paléocène supérieur et de l' Eocene inférieur: *Bulletin de la Société géologique de France*, v. 17, p. 125-147.
- CEBULA, G. T., KUNK, M. J., MEHNERT, H. H., NAESER, C. W., OBRADOVICH, J. O., AND SUTTER J. F., 1986, The Fish Canyon Tuff, a potential standard for the $^{40}\text{Ar}/^{39}\text{Ar}$ and Fission-Track methods: *Terra Cognita*, Abstract with Programs, v. 6, p. 139-140.
- CHAISON, W. P. AND LECKIE, R. M., 1993, High-resolution Neogene planktonic foraminiferal biostratigraphy of ODP Site 806, Ontong Java Plateau (Western Equatorial Pacific): College Station, Proceedings of the Ocean Drilling Program, Scientific Results, v. 130, p. 137-178.
- CHANNELL, J. E. T., RIO, D., SPROVIERI, R., AND GLAÇON, G., 1990, Biomagnetostratigraphic correlations from Leg 107 in the Tyrrhenian Sea: College Station, Proceedings of the Ocean Drilling Program, Scientific Results, v. 107, p. 669-682.
- CHAPRONIERE, G. C. H., STYZEN, M. J., SAGER, W. W., NISHI, H., QUINTERNO, P. J., AND ABRAHAMSEN, N., 1994, Late Neogene biostratigraphic and magnetostratigraphic synthesis, Leg 135: College Station, Proceedings of the Ocean Drilling Program, Scientific Results, v. 135, p. 857-877.
- CHAVE, A. D., 1984, Lower Paleocene-upper Cretaceous magnetostratigraphy, Sites 525, 527, 528, and 529, Deep Sea Drilling Project Leg 74: Washington, D.C., Initial Reports of the Deep Sea Drilling Project, v. 74, p. 525-531.
- CIESIELSKI, P. F., KRISTOFFERSEN, Y., AND OTHERS, 1988, Site 699: College Station, Proceedings of the Ocean Drilling Program, Initial Reports, v. 114, p. 151-254.
- CIFELLI, R., AND SCOTT, G., 1986, Stratigraphic Record of the Neogene Globorotaliid Radiation (Panktonic Foraminifera): *Smithsonian Contributions to Paleobiology* 58, 101 p.
- CITA, M. B., 1973, Pliocene biostratigraphy and chronostratigraphy: Washington, D.C., Initial Reports of the Deep Sea Drilling Project, v. 13, p. 1343-1379.
- CITA, M. B., 1975, The Miocene/Pliocene boundary: history and definition, in Saito, T. and Burckle, L. H., eds., Late Neogene Epoch Boundaries: *Micro-paleontology*, Special Publication, v. 1, p. 1-30.
- CITA, M. B. AND BLOW, W. H., 1969, The biostratigraphy of the Langhian, Serravallian and Tortonian stages in the type-sections in Italy: *Rivista Italiana Paleontologia*, v. 75, p. 549-603.
- CITA, M. B. AND PREMOLI SILVA, I., 1960, Pelagic foraminifera from the type Langhian: *Proceedings of the International Paleontological Union Norden 1960*, part XXII, p. 39-50.

- CITA, M. B. AND PREMOLI SILVA, I., 1968, Evolution of the planktonic foraminiferal assemblages in the stratigraphical interval between the type-Langhian and the type-Tortonian and biozonation of the Miocene of the Piedmont: *Giornale Geologia*, v. 35, p. 1-27.
- CITA, M. B., PREMOLI SILVA, I., AND ROSSI, R., 1965, Foraminifero planktonico del Tortoniano-tipo: *Rivista Italiana Paleontologia*, v. 71, p. 217-308.
- CLEMENT, B. M. AND ROBINSON, F., 1987, The magnetostratigraphy of Leg 94 sediments: Washington D. C., Initial Reports of the Deep Sea Drilling Project, v. 94, p. 635-650.
- COCCIONI, R., MONACO, P., MONECHI, S., NOCCHI, M., AND PARISI, G., 1988, Biostratigraphy of the Eocene-Oligocene boundary at Massignano (Ancona, Italy), in Premoli Silva, I., Coccioni, R., and Montanari, A., eds., The Eocene-Oligocene Boundary in the Marche-Umbria Basin (Italy): Ancona, International Subcommission on Paleogene Stratigraphy, E/O Meeting, Special Publication II, p. 59-74.
- COLALONGO, M. L., DiGRANDE, A., D'ONOFRIO, S., GIANELLI, L., IACCARINO, S., MAZZEI, R., ROMEO, M., AND SALVATORINI, G., 1979, Stratigraphy of Late Miocene Italian sections straddling the Tortonian/Messinian boundary: *Bulletino Società Paleontologia Italiana*, v. 18, p. 258-302.
- CORFIELD, R. M., 1987, Patterns of evolution in Palaeocene and Eocene planktonic Foraminifera, in Hart, M., ed., *The Micropalaeontology of Carbonate Environments*: Chichester, Ellis Horwood, p. 93-110.
- COX, A., DOELL, R. R., AND DALRYMPLE, G. B., 1964, Geomagnetic polarity epochs: *Science*, v. 143, p. 351-352.
- CURRY, D. AND ODIN, G. S., 1982, Dating of the Palaeogene, in Odin, G. S., ed., *Numerical Dating in Stratigraphy*: New York, John Wiley and Sons, v. 1, p. 607-630.
- CUSHMAN, J. A. AND RENZ, H. H., 1947, The foraminiferal fauna of the Oligocene, Ste Croix Formation of Trinidad: *Bulletin of the Western Indies, Special Publication of the Cushman Laboratory*, v. 22, p. 1-46.
- CUSHMAN, J. A. AND STAINFORTH, R. M., 1945, The Foraminifera of the Cipero Marl Formation of Trinidad, British West Indies: Washington, D.C., Cushman Laboratory for Foraminiferal Research Special Publication 14, 75 p.
- DALRYMPLE, G. B., IZETT, G. A., SNEE, L. W., AND OBRADOVICH, J. D., 1993, $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra and total-fusion ages of tektites from Cretaceous-Tertiary Boundary sedimentary rocks in the Beloc Formation, Haiti: United States Geological Bulletin, v. 2065, p. 1-20.
- DEINO, A., TAUXE, L., MONOGHAN, M., AND DRAKE, R., 1990, $^{40}\text{Ar}/^{39}\text{Ar}$ age calibration of the litho- and paleomagnetic stratigraphies of the Ngorora Formation, Kenya: *Journal of Geology*, v. 98, p. 567-587.
- DOWSETT, H., 1988, Diachrony of late Neogene microfossils in the southwest Pacific ocean: application of the graphic correlation method: *Paleoceanography*, v. 3, p. 209-222.
- DOWSETT, H., 1989, Application of the graphic correlation method to Pliocene marine sequences: *Marine Micropalaeontology*, v. 14, p. 3-32.
- DUNCAN, R. A. AND HARGRAVES, R. B., 1990, $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of basement rocks from the Mascarene Plateau, the Chagos Bank, and Maldives Ridge: College Station, Proceedings of the Ocean Drilling Program, Scientific Results, v. 115, p. 43-51.
- EHRENDORFER, T. AND AUBRY, M.-P., 1992, Calcareous nannoplankton changes across the Cretaceous/Paleocene boundary in the southern Indian Ocean (Site 750): College Station, Proceedings of the Ocean Drilling Program, Scientific Results, v. 120, p. 451-470.
- FENNER, J., 1984, Eocene-Oligocene planktic diatom stratigraphy in the low latitudes and the high southern latitudes: *Micropaleontology*, v. 30, p. 319-342.
- FLEISHER, R. L., 1974, Cenozoic planktonic foraminifera and biostratigraphy, Arabian Sea Deep Sea Drilling Project, Leg 23A: Washington, D.C., Initial Reports of the Deep Sea Drilling Project, v. 23, p. 1001-1072.
- GALBRUN, B., 1992, Magnetostratigraphy of upper Cretaceous and lower Tertiary sediments, Sites 761 and 762, Exmouth Plateau, northwest Australia: College Station, Proceedings of the Ocean Drilling Program, Scientific Results, v. 122, p. 699-716.
- GARTNER, S., 1992, Miocene nanofossil chronology in the North Atlantic, DSDP Site 608: *Marine Micropaleontology*, v. 18, p. 307-331.
- GARTNER, S., CHEN, M. P., AND STANTON, R. J., 1983, Late Neogene nanofossil biostratigraphy and paleoceanography of the Northeastern Gulf of Mexico and adjacent areas: *Marine Micropaleontology*, v. 8, p. 17-50.
- GAULTIER, F., CLAUZON, G., SUC, J.-P., CRAVATTE, J., AND VIOLANTI, D., 1994, Age et durée de la crise de salinité messinienne: *Comptes Rendus de l' Académie des Sciences de Paris*, t. 318, séries II, p. 1103-1109.
- GERSONDE, R. AND BURCKLE, L. H., 1990, Neogene diatom biostratigraphy of ODP Leg 113, Weddell Sea (Antarctic Ocean): College Station, Proceedings of the Ocean Drilling Program, Initial Reports, v. 113, 761-789.
- GIANOTTI, A., 1953, Microfaune della serie tortoniana del Rio Mazzapiedi-Castellania (Tortona-Allesandria): *Rivista Italiana Paleontologia, Memoir*, v. 6, p. 167-308.
- GILLOT, P. Y., JEHANNO, C., ROCCHIA, R., AND H. SIGURDSSON, H., 1991, Datation par la méthode potassium-argon de la limite Crétacé-Paléogène en milieu marin: age des verres de Béloc (Haïti): *Comptes Rendus de l' Académie des Sciences de Paris*, t. 313, séries II, p. 193-199.
- GLAÇON, G., VERGAUD GRAZZINI, C., IACCARINO, S., REHALUT, J.-P., RANDRIANASOLO, A., SIERRO, J. V., WEAVER, P., CHANNELL, J., TORII, M., AND HAWTHORNE, T., 1990, Planktonic foraminiferal events and stable isotope records in the upper Miocene, Site 654: College Station, Proceedings of the Ocean Drilling Program, Scientific Results, v. 107, p. 415-427.
- GRADSTEIN, F. M., AGTERBERG, F. P., OGG, J. G., HARDENBOL, J., VEEN P. V., THIERRY, J., AND HUANG, Z., 1994, A Mesozoic time scale: *Journal of Geophysical Research*, v. 99, p. 24.051-24.074.
- GROOT, J. J., JONGE, R. B. G., DE, LANGEREIS, C. G., KATE, W. G. H. Z. TEN, AND SMIT, J., 1989, Magnetostratigraphy of the Cretaceous-Tertiary boundary at Agost (Spain): *Earth and Planetary Science Letters*, v. 94, p. 385-397.
- HAILWOOD, E. A., 1989, The role of magnetostratigraphy in the development of geological time scales: *Paleoceanography*, v. 4, p. 1-18.
- HAILWOOD, E. A. AND CLEMENT, B. M., 1991a, Magnetostratigraphy of Sites 699 and 700, East Georgia Basin: College Station, Proceedings of the Ocean Drilling Program, Scientific Results, v. 114, p. 337-357.
- HAILWOOD, E. A. AND CLEMENT, B. M., 1991b, Magnetostratigraphy of Sites 703 and 704, Meteor Rise, southeastern South Atlantic: College Station, Proceedings of the Ocean Drilling Program, Scientific Results, v. 114, p. 367-385.
- HALL, C. M., YORK, D., AND H. SIGURDSSON, H., 1991, Laser $^{40}\text{Ar}/^{39}\text{Ar}$ step-heating ages from single Cretaceous-Tertiary boundary glass spherules (abs.): *EOS, Transactions, American Geophysical Union*, v. 72, p. 531.
- HAQ, B. U., HARDENBOL, J., AND VAIL, P. R., 1987, The chronology of fluctuating sea level since the Triassic: *Science*, v. 235, p. 1156-1167.
- HAQ, B. U., HARDENBOL, J., AND VAIL, P. R., 1988, Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change, in Wilgus, C. K., Kendall, C. G. St. C., Posamentier, H. W., Ross, C. A., and Van Wagoner, J. C., eds., *Sea Level Changes- An Integrated Approach*: Tulsa, Society of Economic Paleontologists and Mineralogists Special Publication 42, p. 71-108.
- HAQ, B. U., WORSLEY, T. R., BURCKLE, L. H., DOUGLAS, R. G., KEIGWIN, L. D., JR., OPDYKE, N. D., SAVIN, S. M., SOMMER, M. A., III, VINCENT, E., AND WOODRUFF, F., 1980, Late Miocene marine carbon-isotope shift and synchronicity of some phytoplanktonic biostratigraphic events: *Geology*, v. 8, p. 427-431.
- HARDENBOL, J. AND BERGGREN, W. A., 1978, A new Paleogene numerical time scale, in Cohee, G. V., Giassner, M. F., and Hedberg, H. D., eds., *The Geologic Time Scale*: Tulsa, American Association of Petroleum Geology, Studies in Geology 6, p. 213-234.
- HARLAND, W. B., ARMSTRONG, R. L., COX, A. V., CRAIG, L. E., SMITH, A. G., AND SMITH, D. G., 1990, *A Geologic Time Scale 1989*, revised edition: Cambridge, Cambridge University Press, 263 p.
- HARLAND, W. B., COX, A. V., LLEWELLYN, P. G., PICKTON, C. A. G., SMITH, A. G., AND WALTERS, R., 1982, *A Geologic Time Scale*: Cambridge, Cambridge University Press, 131 p.
- HARRIS, W. B. AND FULLAGAR, P. D., 1989, Comparison of Rb-Sr and K-Ar dates of middle Eocene bentonite and glauconite, southeastern Atlantic Coastal Plain: *Geological Society of America Bulletin*, v. 101, p. 573-577.
- HARRIS, W. B. AND FULLAGAR, P. D., 1991, Middle Eocene and Late Oligocene isotopic dates of glauconitic mica from the Santee River area, South Carolina: *Southeastern Geology*, v. 32, p. 1-19.
- HARWOOD, D. M. AND MARUYAMA, T., 1992, Middle Eocene to Pleistocene diatom biostratigraphy of southern Ocean sediment from the Kerguelen Plateau: College Station, Proceedings of the Ocean Drilling Program, Scientific Results, v. 120, p. 683-733.
- HEDBERG, H. D., ed., 1976, *International Stratigraphic Guide: A Guide to Stratigraphic Classification, Terminology and Procedure*: New York, John Wiley and Sons, 200 p.
- HEIRTZLER, J. R., DICKSON, G. O., HERRON, E. M., PITMAN, W. C., AND LE PICHEON, X., 1968, Marine magnetic anomalies, geomagnetic field reversals, and motions of the ocean floor and continents: *Journal of Geophysical Research*, v. 73, p. 2119-2136.
- HERBERT, T. D. AND D'HONDRT, S. L., 1990, Precessional climate cyclicity in Late Cretaceous-early Tertiary marine sediments: a high resolution chronometer of Cretaceous-Tertiary boundary events: *Earth and Planetary Science Letters*, v. 99, p. 263-275.

- HILGEN, F., 1991, Extension of the astronomically calibrated (polarity) time scale to the Miocene/Pliocene boundary: *Earth and Planetary Science Letters*, v. 107, p. 349–368.
- HILGEN, F. AND LANGEREIS, C. G., 1989, Periodicities of CaCO_3 cycles in the Mediterranean Pliocene: discrepancies with the quasi-periods of the Earth's orbital cycles?: *Terra Nova*, v. 1, p. 409–415.
- HILGEN, F. AND LANGEREIS, C. G., 1993, A critical (re)evaluation of the Miocene/Pliocene boundary as defined in the Mediterranean: *Earth and Planetary Science Letters*, v. 118, p. 167–179.
- HODELL, D. A. AND KENNEDY, J. P., 1986, Late Miocene-early Pliocene stratigraphy and paleoceanography of the South Atlantic and southwest Pacific Oceans: a synthesis: *Paleoceanography*, v. 1, p. 285–311.
- HODELL, D., BENSON, R. H., KENT, D. V., BOERSMA, A., AND RAKIC-EL BIED, K., 1994, Magnetostratigraphic, biostratigraphic, and stable isotope stratigraphy of an Upper Miocene drill core from the Sale Briquerie (northwestern Morocco): a high-resolution chronology for the Messinian stage: *Paleoceanography*, v. 9, p. 835–855.
- HUBER, B. T., 1991, Paleogene and early Neogene planktonic foraminifer biostratigraphy of Sites 738 and 744, Kerguelan Plateau (southern Indian Ocean): College Station, *Proceedings of the Ocean Drilling Program, Scientific Results*, v. 119, p. 427–449.
- IACCARINO, S., 1985, Mediterranean Miocene and Pliocene planktic foraminifera, in Bolli, H. M., Saunders, J. B., and Perch-Nielsen, K., *Plankton Stratigraphy*: Cambridge, Cambridge University Press, p. 283–314.
- INOKUCHI, H. AND HEIDER, F., 1992, Magnetostratigraphy of sediments from Sites 748 and 750, Leg 120: College Station, *Proceedings of the Ocean Drilling Program, Scientific Results*, v. 120, p. 247–252.
- IZETT, G. A., DALRYMPLE, G. B., AND SNEE, L. W., 1991, $^{40}\text{Ar}/^{39}\text{Ar}$ age of the Cretaceous-Tertiary boundary tektites from Haiti: *Science*, v. 252, p. 1539–1542.
- IZETT, G. A. AND OBRADOVICH, J. D., 1991, Dating of the Matuyama-Brunhes boundary based on $^{40}\text{Ar}/^{39}\text{Ar}$ ages of the Bishop Tuff and Cerro San Luis Rhyolite (abs.): *Geological Society of America Abstracts with Programs*, v. 23, p. A105.
- IZETT, G. A. AND OBRADOVICH, J. D., 1994, $^{40}\text{Ar}/^{39}\text{Ar}$ age constraints for the Jaramillo normal Subchron and the Matuyama-Brunhes geomagnetic boundary: *Journal of Geophysical Research*, v. 90, p. 2925–2934.
- JENKINS, D. G., 1967, Planktonic foraminiferal zones and new taxa from the lower Miocene to the Pleistocene of New Zealand: *New Zealand Journal of Geology and Geophysics*, v. 10, p. 1064–1078.
- JENKINS, D. G., 1971, New Zealand Cenozoic Planktonic Foraminifera: *Palaeontological Bulletin of the New Zealand Geological Survey*, v. 42, p. 1–278.
- JENKINS, D. G., 1975, Cenozoic planktonic foraminiferal biostratigraphy of the southwestern Pacific and Tasman Sea: Washington, D.C., *Initial Reports of the Deep Sea Drilling Project*, v. 29, p. 449–467.
- JENKINS, D. G., 1992, The paleogeography, evolution and extinction of Late Miocene-Pleistocene planktonic foraminifera from the Southwest Pacific, in Ishizaki, K., and Saito, T., eds., *Centenary of Japanese Micropaleontology, Contributed papers in Honor of Professor Yokichi Takayanagi*: Tokyo, Terra Scientific Publishing Co., p. 27–35.
- JENKINS, D. G., 1993a, Cenozoic southern middle and high latitude biostratigraphy and chronostratigraphy based on planktonic foraminifera, in Kennett, J. P. and Warnke, D. A., eds., *The Antarctic Paleoenvironment: A Perspective on Global Change*: Washington, D.C., American Geophysical Union, Antarctic Research Series, vol. 60, p. 125–144.
- JENKINS, D. G., 1993b, The evolution of the Cenozoic southern high- and mid-latitude planktonic foraminiferal faunas, in Kennett, J. P. and Warnke, D. A., eds., *The Antarctic Paleoenvironment: A Perspective on Global Change*: Washington, D.C., American Geophysical Union, Antarctic Research Series, vol. 60, p. 175–194.
- JENKINS, D. G. AND GAMSON, P., 1993, The late Cenozoic *Globorotalia truncatulinoides* datum-plane in the Atlantic, Pacific and Indian Oceans, in Hailwood, E. A. and Kidd, R. B., eds., *High Resolution Stratigraphy*: London, Geological Society of London Special Publication 70, p. 127–130.
- JENKINS, D. G. AND ORR, W., 1972, Planktonic foraminiferal biostratigraphy of the Eastern Equatorial Pacific: Washington, D.C., *Initial Reports of the Deep Sea Drilling Project*, v. 9, p. 1059–1193.
- JENKINS, D. G., SAUNDERS, J. B., AND CIFELLI, R., 1981, The relationship of *Globigerinoides bisphericus* Todd 1954 to *Praeorbulina sicana* (De Stéphan) 1952: *Journal of Foraminiferal Research*, v. 11, p. 262–267.
- JENKINS, D. G. AND SRINIVASAN, M. S., 1986, Cenozoic planktonic foraminifers from the Equator to the Sub-Antarctic of the southwest Pacific: Washington, D.C., *Initial Reports of the Deep Sea Drilling Project*, v. 90, p. 795–834.
- KEATING, B. H. AND HERRERO-BERVERA, E., 1984, Magnetostratigraphy of the Cretaceous and early Cenozoic sediments of Deep Sea Drilling Project Site 530, Angola: Washington, D.C., *Initial Reports of the Deep Sea Drilling Project*, v. 75, p. 1211–1226.
- KEIGWIN, L. D., JR., 1982, Neogene planktonic foraminifers from Deep Sea Drilling Project Sites 502 and 503: Washington, D.C., *Initial Reports of the Deep Sea Drilling Project*, v. 68, p. 269–288 (see also Appendix, p. 493–495).
- KELLER, G., 1978, Late Neogene biostratigraphy and paleoceanography of DSDP Site 310 Central North Pacific and correlation with the southwest Pacific: *Marine Micropaleontology*, v. 3, p. 97–119.
- KELLER, G., 1979a, Late Neogene planktonic foraminiferal biostratigraphy and paleoceanography of the northwest Pacific DSDP Site 296: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 27, p. 129–154.
- KELLER, G., 1979b, Late Neogene paleoceanography of the North Pacific DSDP Sites 173, 310, and 296: *Marine Micropaleontology*, v. 4, p. 159–172.
- KELLER, G., 1979c, Early Pliocene to Pleistocene planktonic foraminiferal datum levels in the North Pacific: DSDP Sites 173, 310, 296: *Marine Micropaleontology*, v. 4, p. 281–294.
- KELLER, G., 1980a, Early to middle Miocene planktonic foraminiferal datum levels of the equatorial and subtropical Pacific: *Micropaleontology*, v. 6, p. 372–391.
- KELLER, G., 1980b, Middle to late Miocene planktonic foraminiferal datum levels and paleoceanography of the North and southeastern Pacific Ocean: *Marine Micropaleontology*, v. 5, p. 249–281.
- KELLER, G., 1981, Miocene biochronology and paleoceanography of the North Pacific: *Marine Micropaleontology*, v. 6, p. 535–551.
- KELLER, G., 1988, Extinction, survivorship and evolution of planktic foraminifers across the Cretaceous/Tertiary boundary in El Kef, Tunisia: *Marine Micropaleontology*, v. 13, p. 239–263.
- KENNEDY, J. P., 1973, Middle and late Cenozoic planktonic foraminiferal biostratigraphy of the southwest Pacific: DSDP Leg 21: Washington, D.C., *Initial Reports of the Deep Sea Drilling Project*, v. 21, p. 575–640.
- KENNEDY, J. P. AND SRINIVASAN, M., 1983, *Neogene Planktonic Foraminifera: A Phylogenetic Atlas*: Stroudsburg, Hutchinson Ross Publishing Co., 265 p.
- KENNEDY, J. P. AND SRINIVASAN, M. S., 1984, Neogene planktonic foraminiferal datum planes of the South Pacific: mid to equatorial latitudes, in Tsuchi, R. and Ikeye, N., eds., *Pacific Neogene Datum Planes — Contribution to Biostratigraphy and Chronology*: Tokyo, University of Tokyo Press, p. 11–25.
- KENNEDY, J. P. AND WATKINS, N. D., 1974, Late Miocene-early Pliocene paleomagnetic stratigraphy, paleoclimatology and biostratigraphy in New Zealand: *Geological Society America Bulletin*, v. 85, p. 1385–1398.
- KLITGORD, K. D., HEUSTIS, S. P., MUDIE, J. D., AND PARKER, R. L., 1975, An analysis of near-bottom magnetic anomalies: sea floor spreading and the magnetized layer: *Geophysical Journal of the Royal Astronomical Society*, v. 43, p. 387–424.
- KNOX, R. W. O'B., HINE, N. M., AND ALI, J., 1994, New information on the age and sequence stratigraphy of the type Thanetian of southeast England: *Newsletters in Stratigraphy*, v. 30, p. 45–60.
- KRUGSMAN, W., HILGEN, F. J., LANGEREIS, C. G., AND ZACHARIASSE, W. J., 1994, The age of the Tortonian/Messinian boundary: *Earth and Planetary Sciences Letters*, v. 121, p. 533–547.
- LABRECQUE, J. L., HSU, K. J., CARMAN, M. F. J., KARPOFF, A. M., MCKENZIE, J. A., PERCIVAL, S. F. P., PETERSEN, N. P., PISCOTTO, K. A., SCHREIBER, E., TAUXE, L., TUCKER, P., WEISSERT, H. J., AND WRIGHT, R., 1983, DSDP Leg 73: Contributions to Paleogene stratigraphy in nomenclature, chronology and sedimentation rates: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 42, p. 91–125.
- LABRECQUE, J. L., KENT, D. V., AND CANDE, S. C., 1977, Revised magnetic polarity time scale for the Late Cretaceous and Cenozoic time: *Geology*, v. 5, p. 330–335.
- LANG, T. H. AND WISE, S. W., JR., 1987, Neogene and Paleocene-Maestrichtian calcareous nannofossil stratigraphy, Deep Sea Drilling Project Sites 604 and 605, upper continental rise of New Jersey: sedimentation rates, hiatuses, and correlations with seismic stratigraphy: Washington, D.C., *Initial Reports of the Deep Sea Drilling Project*, v. 93, p. 661–683.
- LANGEREIS, C. G. AND DEKKERS, M. J., 1992, Paleomagnetism and rock magnetism of the Tortonian-Messinian boundary stratotype at Falconara, Sicily: *Physics of the Earth and Planetary Interiors*, v. 71, p. 100–111.
- LANGEREIS, C. G. AND HILGEN, F. G., 1991, The Rosello composite: a Mediterranean and global reference section for the Early to early Late Pliocene: *Earth and Planetary Science Letters*, v. 104, p. 211–225.

- LANGEREIS, C. G., van HOOF, A. A. M., and HILGEN, F. J., 1994, Steadyng the rates: *Nature*, v. 369, p. 615.
- LANGEREIS, C. G., ZACHARIASSE, W. J., and ZIJDERVELD, J. D. A., 1984, Late Miocene magnetobiostratigraphy of Crete: *Marine Micropaleontology*, v. 8, p. 261–281.
- LARSON, R. L. and PITMAN, W. C., 1972, Worldwide correlation of Mesozoic magnetic anomalies, and its implications: *Geological Society of America Bulletin*, v. 83, p. 3645–3662.
- LECKIE, M., FARNHAM, C., and SCHMIDT, M. G., 1993, Oligocene planktonic foraminiferal biostratigraphy of ODP Hole 130–803D (Ontong Java Plateau) and ODP Hole 101–628A (Little Bahama Bank) and comparison with the southern high latitudes: College Station, *Proceedings of the Ocean Drilling Program, Scientific Results*, v. 130, p. 113–136.
- LEONOV, G. P. and ALIMARINA, V. P., 1961, Stratigraphy and planktonic foraminifera of the Cretaceous-Paleogene “Transition” beds of the central part of the North Caucasus: Collected Papers Geological Faculty, University of Moscow, to XXI International Geological Congress, p. 29–60 (in Russian with an extensive English abstract).
- LEONOV, G. P. and ALIMARINA, V. P., 1964, Stratigraphical problems of the Paleogene deposits of the northwestern Caucasus: Moscow, Moscow University Press, 204 p.
- LI, Q., RADFORD, S. S., BANNER, F. T., 1992, Distribution of microperforate tenuitellid planktonic foraminifers in Holes 747A and 749B, Kerguelen Plateau: College Station, *Proceedings of the Ocean Drilling Program, Scientific Results*, v. 120, p. 569–602.
- LIU, C., 1993, Uppermost Cretaceous-Lower Paleocene stratigraphy and turnover of planktonic foraminifera across the Cretaceous/Paleogene boundary: Unpublished Ph.D. Dissertation, Rutgers University, New Brunswick, 181 p.
- LOUTIT, T. and KENNEDY, J. P., 1979, Application of carbon isotope stratigraphy to late Miocene shallow marine sediments, New Zealand: *Science*, v. 204, p. 1196–1199.
- LOWRIE, W. and ALVAREZ, W., 1981, One hundred million years of geomagnetic polarity history: *Geology*, v. 9, p. 392–397.
- LOWRIE, W., ALVAREZ, W., NAPOLEONE, G., PERCH-NIELSEN, K., PREMOLI SILVA, I., and TOUMARKINE, M., 1982, Paleogene magnetic stratigraphy in Umbrian pelagic carbonate rocks: The Contessa sections, Gubbio: *Geological Society of America Bulletin*, v. 93, p. 414–432.
- LUTERBACHER, H.-P. and PREMOLI SILVA, I., 1964, Biostratigrafia del limite Cretaceo-Terziario nell’Appennino centrale: *Rivista Italiana Paleontologia Stratigraphia*, v. 70, p. 67–128.
- MACFADDEN, B. J., SWISHER, C. C., OPDYKE, N. D., and WOODBURN, M. O., 1990, Paleomagnetism, geochronology, and possible tectonic rotation of the middle Miocene Barstow Formation, Mojave Desert, southern California: *Geological Society of America Bulletin*, v. 102, p. 478–493.
- MALMGREN, B. and KENNEDY, J. P., 1982, The potential of morphometrically based phylozonation: application of a Late Cenozoic planktonic foraminiferal lineage: *Marine Micropaleontology*, v. 7, p. 285–296.
- MANIVIT, H., 1984, Paleogene and upper Cretaceous calcareous nannofossils from Deep Sea Drilling Project Leg 74: Washington, D.C., *Initial Reports of the Deep Sea Drilling Project*, v. 74, p. 475–499.
- MANKINEN, E. A., and DALRYMPLE, G. B., 1979, Revised geomagnetic polarity time scale for the interval 0–5 my B.P.: *Journal of Geophysical Research*, v. 84, p. 615–626.
- MARTINI, E., 1971, Standard Tertiary and Quaternary calcareous nannoplankton zonation, in Farinacci, A., ed., *Proceedings of the Second Planktonic Conference, Roma 1970*: Roma, Tecnoscienza, p. 739–785.
- MAYER, L. C., PISIAS, N., and JANACEK, T., and OTHERS, 1992, Leg 138: College Station, *Proceedings of the Ocean Drilling Program, Initial Reports*, v. 138, 1462 p.
- MCDougall, I., BROWN, F. H., CERLING, T. E., and HILLHOUSE, J. W., 1992, A reappraisal of the geomagnetic polarity time scale to 4 Ma using data from the Turkana Basin, East Africa: *Geophysical Research Letters*, v. 19, p. 2349–2352.
- MCDougall, I., KRISTJANSSON, L., and SAEMUNDSSON, K., 1984, Magnetobiostratigraphy and geochronology of northwest Iceland: *Journal of Geophysical Research*, v. 89, p. 7029–7060.
- MCINTOSH, W. C., GEISSMAN, J. W., CHAPIN, C. E., KUNK, M. J., and HENRY, C. D., 1992, Calibration of the latest Eocene-Oligocene geomagnetic polarity time scale using $^{40}\text{Ar}/^{39}\text{Ar}$ ignimbrites: *Geology*, v. 20, p. 459–463.
- MCWILLIAMS, M. O., BAKSI, A. K., and BAADSGAARD, H., 1991a, High resolution $^{40}\text{Ar}/^{39}\text{Ar}$ ages from Cretaceous-Tertiary boundary bentonites in Western North America (abs.): IGCP Projects 216, 293, 303, Event Markers in Earth History, p. 53.
- MCWILLIAMS, M. O., BAKSI, A. K., and BAADSGAARD, H., 1991b, New $^{40}\text{Ar}/^{39}\text{Ar}$ ages from K-T boundary bentonites in Montana and Saskatchewan (abs.): *EOS, Transactions, American Geophysical Union*, v. 72, p. 301.
- MCWILLIAMS, M. O., BAKSI, A. K., BOHOR, B. F., IZETT, G. A., and MURALI, A. V., 1992, High precision relative ages of K/T boundary events in North America and Deccan Trap volcanism in India (Abs): *EOS, Transactions, American Geophysical Union*, v. 73, p. 363.
- MILLER, K. G., AUBRY, M.-P., KHAN, M. J., MELILLO, A., KENT, D. V., and BERGGREN, W. A., 1985, Oligocene-Miocene biostratigraphy, magnetostratigraphy, and isotopic stratigraphy of the western North Atlantic: *Geology*, v. 13, p. 257–261.
- MILLER, K. G., FEIGENSON, M. D., WRIGHT, J. D., and CLEMENT, B. M., 1991, Miocene isotope reference section, Deep Sea Drilling Project Site 608: an evaluation of isotope and biostratigraphic resolution: *Paleoceanography*, v. 6, p. 33–52.
- MILLER, K. G., THOMPSON, P. R., and KENT, D. V., 1993, Integrated late Eocene-Oligocene stratigraphy of the Alabama coastal Plain: Correlation of hiatuses and stratal surfaces to glacioeustatic lowerings: *Paleoceanography*, v. 8, p. 313–331.
- MILLER, K. G., WRIGHT, J. D., FOSSEN, M. C., VAN, and KENT, D. V., 1994, Miocene stable isotopic stratigraphy and magnetostratigraphy of Buff Bay, Jamaica: *Geological Society of America Bulletin*, v. 106, p. 1605–1620.
- MOLINA, E., 1986, Description and biostratigraphy of the main reference section of the Eocene/Oligocene boundary in Spain: Fuente Caldera section, in Pomerol, C. and Premoli Silva, I., eds., *Terminal Eocene Events*: Amsterdam, Elsevier, *Developments in Stratigraphy*, v. 9, p. 53–63.
- MOLINA, E., CANUDO, J. I., GUERNET, C., McDougall, K., OTIZ, N., PASCUAL, J. O., PARES, J. M., SAMSO, J. M., SERRA-KIEL, J., and TOSQUELLA, J., 1992, The stratotypic Ilerdian revisited: integrated stratigraphy across the Paleocene/Eocene boundary: *Revue de Micropaléontologie*, v. 35, p. 143–156.
- MOLINA, E., MONACO, P., NOCCHI, M., and PARISI, G., 1986, Biostratigraphic correlation between the Central Subbetic (Spain) and Umbro-Marchean (Italy) pelagic sequences at the Eocene/Oligocene boundary using foraminifera, in Pomerol, C. and Premoli Silva, I., eds., *Terminal Eocene Events, Developments in Stratigraphy*, v. 9: Amsterdam, Elsevier Science Publishers, p. 75–85.
- MONECHI, S., 1985, Campanian to Pleistocene calcareous nannofossil stratigraphy from the northwest Pacific Ocean, Deep Sea Drilling Project Leg 86: Washington, D.C., *Initial Reports of the Deep Sea Drilling Project*, v. 86, p. 301–36.
- MONECHI, S., 1986, Calcareous nannofossil events around the Eocene-Oligocene boundary in the Umbrian sections (Italy): *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 57, p. 61–69.
- MONECHI, S., BLEIL, U., and BACKMAN, J., 1985, Magnetobiochronology of late Cretaceous—Paleogene and late Cenozoic pelagic sedimentary sequences from the northwest Pacific (Deep Sea Drilling Project, Leg 86, Site 577): Washington, D.C., *Initial Reports of the Deep Sea Drilling Project*, v. 86, p. 787–797.
- MONECHI, S. and THIERSTEIN, H., 1985, Late Cretaceous- Eocene nannofossil and magnetostratigraphic correlations near Gubbio, Italy: *Marine Micropaleontology*, v. 9, p. 419–440.
- MONTANARI, A., DEINO, A., COCCIONI, R., LANGENHEIM, V. E., CAPO, R., and MONECHI, S., 1991, Geochronology, Sr isotope analysis, magnetostratigraphy, and planktonic stratigraphy across the Oligocene-Miocene boundary in the Contessa section (Gubbio, Italy): *Newsletters in Stratigraphy*, v. 23, p. 151–180.
- MONTANARI, A., DEINO, A., DRAKE, R., TURRIN, B., DEPAOLO, D., ODIN, G., CURTIS, G. H., ALVAREZ, W., and BICE, D. M., 1988, Radioisotopic dating of the Eocene/Oligocene boundary in the pelagic sequence of the northern Apennines, in Premoli Silva, I., Coccioni, R., and Montanari, A., eds., *International Union of Geological Sciences Commission on Stratigraphy: Ancona, International Subcommission on Paleogene Stratigraphy report*, p. 195–208.
- MONTANARI, A., DEINO, A., LANGENHEIM, V. E., and COCCIONI, R., 1990, $^{40}\text{Ar}/^{39}\text{Ar}$ laser-fusion dating of magnetic polarity reversals and planktonic foraminiferal events across the Aquitanian-Burdigalian boundary at Gubbio, Italy (abs.): *EOS, Transactions, American Geophysical Union*, v. 71, p. 1295.
- MOORE, T. C., Jr., RABINOWITZ, P. D., and OTHERS, 1984, Site 528: Washington D. C., *Initial Reports of the Deep Sea Drilling Project*, v. 74, p. 307–405.
- MOROZOVA, V. G., 1960, Zonal stratigraphy of Danian-Montian beds of the U.S.S.R. and the boundary between the Cretaceous and the Paleogene: In-

- ternational Geological Congress, XXI Session, Doklady Soviet Geologists, v. 5, p. 83–100 (in Russian, extended English abstract).
- MOSNA, S. AND MICHELETTI, A., 1968, Microfauna del "Serravalliano", Committee on Mediterranean Neogene Stratigraphy, Proceedings of IV Session: Giornale di geologia, v. 35, p. 183–189.
- MOULLADE, M., 1987, Deep Sea Drilling Project Leg 93: biostratigraphic synthesis: Washington, D.C., Initial Reports of the Deep Sea Drilling Project, v. 93, p. 1271–1282.
- MÜLLER, C., 1985, Biostratigraphic and paleoenvironmental interpretation of the Goban Spur region based on a study of calcareous nannoplankton: Washington D. C., Initial Reports of the Deep Sea Drilling Project, v. 80, p. 573–599.
- NAPOLEONE, G., PREMOLI SILVA, I., HELLER, F., CHELI, P., COREZZI, S., 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.
- NEDERBRAGT, A. J. AND VAN HINTE, J. E., 1987, Biometric analysis of *Planorotalites pseudomenardii* (upper Paleocene) at Deep Sea Drilling Project Site 605, northwestern Atlantic: Washington, D.C. Initial Reports of the Deep Sea Drilling Project, v. 93, p. 577–591.
- NESS, G., LEVI, S., AND COUCH, R., 1980, Marine magnetic anomaly timescales for the Cenozoic and Late Cretaceous: A precis, critique, and synthesis: Reviews of Geophysics and Space Physics, v. 18, p. 753–770.
- NOCCHI, M., PARISI, G., MONACO, P., MONECHI, S., MANDILE, M., NAPOLEONE, G., RIPEPE, M., ORLANDO, M., PREMOLI SILVA, I., AND BICE, D. M., 1986, The Eocene-Oligocene boundary in the Cambrian pelagic regression, in Pomerol, C. and Premoli Silva, I., eds., Terminal Eocene Events: Amsterdam, Elsevier, Developments in Stratigraphy 9, p. 25–40.
- OBRADOVICH, J. D., 1984, An overview of the measurement of geologic time and the paradox of geologic time scales: Stratigraphy, v. 1, p. 11–30.
- OBRADOVICH, J. D., 1993, A Cretaceous time scale, in Caldwell, W. G. E. and Kauffman, E. G., eds., The Evolution of the Western Interior Basin: Ottawa, Geological Society of Canada Special Paper 39, p. 379–396.
- OBRADOVICH, J. O., DOCKERY, D. D., AND SWISHER, C. C., 1993, $^{40}\text{Ar}/^{39}\text{Ar}$ ages of bentonites in the upper part of the Yazoo Formation (upper Eocene), west-central Mississippi: Mississippi Geology, v. 14, p. 1–9.
- ODIN, G. S., ed., 1982, Numerical Dating in Stratigraphy, Part II: New York, John Wiley and Sons, p. 63–1040.
- ODIN, G. S. AND LUTERBACHER, H., 1992, The age of the Paleogene stage boundaries, in Luterbacher, H., ed., Paleogene Stages and Their Boundaries: Neues Jahrbuch für Geologie und Paläontologie, v. 186, p. 21–48.
- ODIN, G. S. AND MONTANARI, A., 1989, Age radiométrique et stratotype de la limite Eocène-Oligocène: Comptes Rendus de l' Académie des Sciences de Paris, t. 309, series II: 1939–1945.
- ODIN, G. S. AND ODIN, C., 1990, Echelle numérique des temps géologiques: Géochronique, v. 35, p. 12–21.
- OKADA, H. AND BUKRY, D., 1980, Supplementary modification and introduction of code numbers to the low-latitude coccolith biostratigraphic zonation: Marine Micropaleontology, v. 5, p. 321–325.
- OLAFSSON, G., 1989, Quantitative calcareous nannofossil biostratigraphy of upper Oligocene to middle Miocene sediment from ODP Hole 667A and middle Miocene sediment from DSDP Site 574: College Station, Proceedings of the Ocean Drilling Program, Scientific Results, v. 108, p. 9–22.
- OLAFSSON, G., 1991, Quantitative calcareous nannofossil biostratigraphy and biochronology of early through late Miocene sediment from DSDP Hole 608: Meddelanden från Stockholms Universitets Institution för Geologi och Geokemi, v. 203, 23 pp.
- OLSSON, R. K., HEMLEBEN, C., BERGGREN, W. A., AND LIU, C., 1992, Wall texture classification of planktonic foraminifera genera in the lower Danian: Journal of Foraminiferal Research, v. 22, p. 195–213.
- ONOFRIO, d' S., GIANELLI, L., IACCARINO, S., MORLOTTI, E., ROMEO, M., SALVATORINI, G., SAMPO, M., AND SPROVIERI, R., 1975, Planktonic foraminifera from some Italian sections and the problem of the lower boundary of the Messinian: Bollettino Società Paleontologia Italiana, v. 14, p. 177–196.
- OPDYKE, N. D., BURCKLE, L. H., AND TODD, A., 1974, The extension of the magnetic time scale in sediments of the Central Pacific Ocean: Earth and Planetary Science Letters, v. 22, p. 300–306.
- ORUE-ETXEBARRIA, X., BACETA, J. I., PUJALTE, V., NUNEZ-BETELU, K., SERRAKIEL, J., APELLANIZ, E., AND PAYROS, A., 1992, Evaluating prospective Paleocene-Eocene boundary parastratotypes in the deep water Basque Basin, western Pyrenees: Ermita and Trabakua Pass sections, Biscay, Basque Basin (abs.): Zaragoza, IGCP Project 308: Paleocene/Eocene Boundary Events, International Meeting and Field Conference, Abstract Volume, p. 9 and 10 page addendum.
- PAK, D. AND MILLER, K. G., 1993, Late Paleocene to early Eocene benthic foraminiferal stable isotopes and assemblages: implications for deep-water circulation: Paleoceanography, v. 7, p. 405–422.
- PERCIVAL, S. F., 1984, Late Cretaceous to Pleistocene calcareous nannofossils from the South Atlantic, Deep Sea Drilling Project 73: Washington, D.C., Initial Reports of the Deep Sea Drilling Project, v. 73, p. 391–424.
- PERMANENT INDERDEPARTMENTAL STRATIGRAPHIC COMMISSION, 1963, Decision of the Permanent Interdepartmental Stratigraphic Commission on the Paleogene of the USSR: Sovetskaya Geologiya, v. 6, p. 145–154.
- PITMAN, W. C., HERRON, E. M., AND HEITZLER, J. R., 1968, Magnetic anomalies in the Pacific and sea floor spreading: Journal of Geophysical Research, v. 73, p. 2069–2085.
- POAG, W. C. AND AUBRY, M.-P., 1995, Upper Eocene impactites of the U.S. East Coast: Depositional origins, biostratigraphic framework, and correlation: Palaios, v. 10, p. 16–43.
- POMEROL, C. AND PREMOLI SILVA, I., eds., 1986, Terminal Eocene Events: Amsterdam, Elsevier, Developments in Paleontology and Stratigraphy 9, 420 p.
- POORE, R. Z. AND BERGGREN, W. A., 1974, Pliocene biostratigraphy of the Labrador Sea: calcareous plankton: Journal of Foraminiferal Research, v. 4, p. 91–108.
- POORE, R. Z. AND BERGGREN, W. A., 1975, Late Cenozoic planktonic foraminiferal biostratigraphy and paleoecology of Hatton-Rockall Basin, DSDP Site 116: Journal of Foraminiferal Research, v. 5, p. 270–293.
- POORE, R. Z., TAUXE, L., PERCIVAL, JR., S. F., LABRECQUE, J. L., 1982, Late Eocene-Oligocene magnetostratigraphy and biostratigraphy at South Atlantic DSDP Site 522: Geology, v. 10, p. 508–511.
- POORE, R. Z., TAUXE, L., PERCIVAL, JR., S. F., LABRECQUE, J. L., WRIGHT, R., PETERSON, N. P., SMITH, C. C., TUCKER, P., AND HSU, K. J., 1983, Late Cretaceous-Cenozoic magnetostratigraphy and biostratigraphy of the South Atlantic Ocean: DSDP Leg 73: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 42, p. 127–149.
- POORE, R. Z., TAUXE, L., PERCIVAL, JR., S. F., LABRECQUE, J. L., WRIGHT, R., PETERSEN, N. P., SMITH, C. C., TUCKER, P., AND HSU, K. J., 1984, Late Cretaceous-Cenozoic magnetostratigraphy and biostratigraphic correlations of the South Atlantic Ocean: Washington, D.C., Initial Reports of the Deep Sea Drilling Project, v. 73, p. 645–656.
- POSPICHAL, J. J., DEHN, J., DRISCOLL, N. W., EIJDEN, VAN, A. J. M., FARRELL, J. W., FOURTANIER, E., GAMSON, P., GEE, J., JANACEK, T. R., JENKINS, D. G., KLOOTWIJK, L. C., NOMURA, R., OWEN, R. M., REA, D., RESIWATI, P., SMIT, J., AND SMITH, G., 1991, Cretaceous-Paleogene biomagnetostratigraphy of Sites 752–755, Broken Ridge: A synthesis: College Station, Proceedings of the Ocean Drilling Program, Scientific Results, v. 121, p. 721–741.
- POSPICHAL, J. J. AND WISE, S. W., 1990, Paleocene to middle Eocene calcareous nannofossils of ODP Sites 689 and 690, Maud Rise, Weddell Sea: College Station, Proceedings of the Ocean Drilling Program, Scientific Results, v. 113, p. 613–638.
- PREMOLI SILVA, I. AND BOLLI, H. M., 1973, Late Cretaceous to Eocene planktonic foraminifera and stratigraphy of Leg 15 sites in the Caribbean Sea: Washington, D.C., Initial Reports of the Deep Sea Drilling Project, v. 15, p. 449–547.
- PREMOLI SILVA, I., COCCIONI, R., AND MONTANARI, A., eds., 1988b, The Eocene-Oligocene Boundary in the Marche-Umbria Basin (Italy): Ancona, International Union of Geological Sciences Commission on Stratigraphy, International Subcommission on Paleogene Stratigraphy Report, 268 p.
- PREMOLI SILVA, I., ORLANDO, M., MONECHI, S., MADILE, M., NAPOLEONE, G., AND RIPEPE, M., 1988a, Calcareous plankton biostratigraphy and magnetostratigraphy at the Eocene/Oligocene transition in the Gubbio area, in Premoli Silva, I., Coccioni, R., and Montanari, A., eds., The Eocene-Oligocene Boundary in the Marche-Umbria Basin (Italy): Ancona, International Union of Geological Sciences Commission on Stratigraphy, International Subcommission on Paleogene Stratigraphy report, p. 137–161.
- PROTHERO, D. R., 1994, The Eocene-Oligocene Transition: Paradise Lost: New York, Columbia University Press, 291 p.
- PROTHERO, D. R. AND SWISHER, C. C., III, 1992, Magnetostratigraphy and geochronology of the terrestrial Eocene-Oligocene transition in North America, in Prothero, D. R. and Berggren, W. A., eds., Eocene-Oligocene Climatic and Biotic Evolution: Princeton, Princeton University Press, p. 46–73.
- PROTO DECIMA, F. AND BOLLI, H. M., 1970, Evolution and variability of *Orbulinoides beckmanni* (Saito): Eclogae geologiae Helvetiae, v. 63, p. 883–905.
- PUJOL, C., 1983, Cenozoic planktonic foraminiferal biostratigraphy of the southwestern Atlantic (Rio Grande Rise): Deep Sea Drilling Project Leg 72:

- Washington, D.C., Initial Reports of the Deep Sea Drilling Project, v. 72, p. 623–673.
- RAFFI, I. AND FLORES, J.-A., 1995, Pleistocene through Miocene calcareous nannofossils from eastern equatorial Pacific Ocean (ODP leg 138): College Station, Proceedings of the Ocean Drilling Program, Scientific Results, v. 138, (in press).
- RAFFI, I., RIO, D., d'AFRI, A., FORNACIARI, E., AND ROCCHETTI, S., 1995, Quantitative distribution patterns and biomagnetostriatigraphy of middle and late Miocene calcareous nannofossils from equatorial Indian and Pacific Oceans (legs 115, 130, and 138): College Station, Proceedings of the Ocean Drilling Program, Scientific Results, v. 138, (in press).
- RENNE, P. R., DEINO, A. L., WALTER, R. C., TURRIN, B. D., SWISHER, C. C., BECKER, T. A., CURTIS, G. H., SHARP, W. D., AND JAOUNI, A. R., 1994, Intercalibration of astronomical and radioisotopic time: Geology, v. 22, p. 783–786.
- RENNE, P. R., WALTER, R., VEROSUB, K., SWEITZER, M., AND ARONSON, J., 1993, New Data from Hadar (Ethiopia) support orbitally tuned timescale to 3.3 Ma: Geophysical Research Letters, v. 20, p. 1067–1070.
- RIO, D., FORNACIARI, E., AND RAFFI, I., 1990, Late Oligocene through early Pleistocene calcareous nannofossils from western equatorial Indian Ocean (Leg 115): College Station, Proceedings of Ocean Drilling Program, Scientific Results, v. 115, p. 175–235.
- ROBERTS, A. P., TURNER, G. M., AND VELLA, P. P., 1994, Magnetostratigraphic chronology of late Miocene to early Pliocene biostratigraphic and oceanographic events in New Zealand: Geological Society of America Bulletin, v. 106, p. 665–683.
- ROSENKRANTZ, A., 1924, De københavnske Grønsandslag og deres Placering i den danske Lagrække (med et Skema over det danske Palaeocaen): Meddelelser fra Dansk Geologisk Forening, v. 6, p. 22–39.
- RYAN, W. B. F., CITA, M. B., RAWSON, M. D., BURCKLE, L. H., AND SAITO, T., 1974, A paleomagnetic assignment of Neogene stage boundaries and the development of isochronous datum planes between the Mediterranean, the Pacific and Indian Oceans in order to investigate the response of the World Ocean to the Mediterranean “Salinity Crisis”: Rivista Italiana Paleontologia, v. 80, p. 631–688.
- SAINT-MARC, P., 1987, Biostratigraphic and paleoenvironmental study of Paleocene benthic and planktonic foraminifers, Site 605, Deep Sea Drilling Project Leg. 93: Washington, D.C., Initial Reports of the Deep Sea Drilling Project, v. 93, p. 539–547.
- SAITO, T., 1984, Planktonic foraminiferal datum planes for biostratigraphic correlation of Pacific Neogene sequences — 1982 status report, in Ikebe, N. and Tsuchi, R., eds., Pacific Neogene Datum Planes: Tokyo, University of Tokyo Press, p. 3–10.
- SALVADOR, A., ed., 1994, International Stratigraphic Guide: Boulder, International Union of Geological Sciences and the Geological Society of America, 214 p.
- SAMSON, S. D. AND ALEXANDER, JR., E. C., 1987, Calibration of the interlaboratory $^{40}\text{Ar}/^{39}\text{Ar}$ standard, MMhb-I: Chemical Geology, Isotope Geoscience Section, v. 66, p. 27–34.
- SAUNDERS, J. B. AND BOLLI, H. M., 1983, Trinidad's contribution to world biostratigraphy: Trinidad, Transactions of the Fourth Latin American Congress, 1979.
- SCHLICH, R., WISE, S. W., JR., AND OTHERS, Site 750: College Station, Proceedings of the Ocean Drilling Program, Initial Reports, v. 120, p. 277–337, 569–619.
- SCHNEIDER, D., 1995, Paleomagnetism of some ODP Leg 138 sediments: Miocene magnetostratigraphic miscellany: College Station, Proceedings of the Ocean Drilling Program, Scientific Results, v. 138, (in press).
- SCHOCH, H. M., 1989, Stratigraphy: Principles and Methods: New York, Van Nostrand and Reinhold, 375 p.
- SCOTT, G. H., 1982, Tempo and stratigraphic record of speciation in *Globorotalia punciculata*: Journal of Foraminiferal Research, v. 12, p. 1–12.
- SCOTT, G. H., BISHOP, S. AND BURT, B. J., 1990, Guide to Some Neogene Globorotaliids (Foraminiferida) from New Zealand: New Zealand Geological Survey Paleontological Bulletin, v. 61, 135 p.
- SELLI, R., 1960, The Mayer-Eymar Messianian, 1867, proposal for a neostotype: International Geological Congress, Report 21st Session, Norden, p. 311–333.
- SHACKLETON, N. J., BERGER, A., AND PELTIER, W. R., 1990, An alternative astronomical calibration of the lower Pleistocene timescale based on ODP Site 677: Transactions of the Royal Society of Edinburgh, Earth Sciences, v. 81, p. 251–261.
- SHACKLETON, N. J., CROWHURST, S., HAGELBERG, T., PISIAS, N. G., AND SCHNEIDER, D. A., 1995, A new Late Neogene time scale: Application to Leg 138 Sites: College Station, Proceedings of the Ocean Drilling Program, Scientific Results, v. 138, p. 73–101.
- SHACKLETON, N. J. AND MEMBERS OF THE SHIPBOARD SCIENTIFIC PARTY, 1984, Accumulation rates in leg 74 sediments: Washington, D.C., Initial Reports of the Deep Sea Drilling Project, v. 74, p. 621–644.
- SHARPTON, V. L., DALRYMPLE, G. B., MARTIN, L. E., RYDER, SCHURAYTZ, B. C., AND FUCUGAUCHI, J. URRUTIA, 1992, New links between the Chicxulub impact structure and the Cretaceous/Tertiary boundary: Nature, v. 359, p. 819–821.
- SHIBATA, K., NISHIMURA, S. AND CHINZEI, K., 1984, Radiometric dating related to Pacific Neogene planktonic datum planes, in Ikebe, N. and Tsuchi, R., eds., Pacific Neogene Datum Planes: Contributions to Biostratigraphy and Chronology: Tokyo, Tokyo University Press, p. 85–89.
- SHUTSKAYA, E. K., 1953, The subdivision of the Kuban and Elburgan Horizons of the northern Caucasus by means of Globigerinas: Biulletin Moskovski Obschchii ispytatelni prirody, otdel geologiya, v. 28, p. 71–79 (in Russian).
- SHUTSKAYA, E. K., 1956, Stratigraphy of the lower horizons of the Paleogene in the central Precaucasus according to the foraminifera: Institut Geologicheskii Nauk Akademii Nauk SSSR, Trudy, v. 164, geol. ser., no. 70, p. 3–114 (in Russian).
- SHUTSKAYA, E. K., 1960a, Stratigraphy of the Early Paleogene of Crimea and the northern Precaucasus, in Yanshin, A. L., Vyalov, O. S., Dolgopolov, N. N., and Menner, V. V., eds., Paleogene Deposits of the Southern European USSR: Moscow, Izdatel'stvo Akademii Nauk, p. 207–229 (in Russian).
- SHUTSKAYA, E. K., 1960b, Stratigraphy and Facies of the Lower Paleogene of the Precaucasus: Gostoptekhizdat, 104 p. (in Russian).
- SHUTSKAYA, E. K., 1962, Foraminifera of the Danian and Paleocene in pelagic facies of the Crimea, Precaucasus and Transcaspian regions: Biulletin Moskovski Obschchii ispytatelni prirody, otdel geologiya, v. 37, p. 126–127 (in Russian).
- SHUTSAKAYA, E. K., 1965, Nizhnii paleogen Kryma, Predkavkaz'ya i zapadnoi chasti Srednei Azii: Geologicheskaya Institut Nauk, Akademii Nauk SSSR, Gosgeolkoma SSSR, Moskva.
- SHUTSAKAYA, E. K., 1970, Stratigrafiya, foraminifery i paleogeografiya nizhnego paleogena Kryma, predkavkaz'ya i zapadnoi chasti srednei Azii. Vsesoyuznyi nauchno-issledovatel'skii geologo-razvedochnyi neftyanoi institut (VNIGRI): Trudy, v. 70, 256 p.
- SIESSER, W. G. AND BRALOWER, T. J., 1992, Cenozoic calcareous nannofossil biostratigraphy on the Exmouth Plateau, eastern Indian Ocean: College Station, Proceedings of the Ocean Drilling Program, Scientific Results, v. 122, p. 601–631.
- SMIT, J., 1982, Extinction and evolution of planktonic foraminifera at the Cretaceous/Tertiary boundary after a major impact, in Silver, L. T. and Schultz, P. H., eds., Geological Implications of Impacts of Large Asteroids and Comets on the Earth: Boulder, Geological Society of America Special Paper 190, p. 329–352.
- SNYDER, S. W. AND WATERS, V. J., 1985, Cenozoic planktonic foraminiferal biostratigraphy of the Goban Spur region, Deep Sea Drilling Project 80: Washington, D.C. Initial Reports of the Deep Sea Drilling Project, v. 80, p. 439–472.
- SPELL, T. L. AND HARRISON, T. M., 1993, $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of the post-Valles Caldera rhyolites, Jemez volcanic field, New Mexico: Journal of Geophysical Research, v. 98, p. 8031–8051.
- SPELL, T. L. AND McDougall, I., 1992, Revisions to the age of the Brunhes-Matuyama boundary and the Pleistocene geomagnetic polarity time scale: Journal of Geophysical Research, v. 94, p. 10370–10396.
- SPENCER-CERVATO, C., THIERSTEIN, H. R., LAZARUS, D. B., AND BECKMAN, J.-P., 1994, How synchronous are Neogene marine plankton events?: Paleoceanography, v. 9, p. 739–763.
- SPIEGLER, D. AND JANSEN, E., 1989, Planktonic foraminifera biostratigraphy of Norwegian Sea sediments; ODP Leg 104: College Station, Proceedings of the Ocean Drilling Program, Scientific Results, v. 104, p. 681–696.
- SPIESS, V., 1990, Cenozoic magnetostratigraphy of Leg 113 drill sites, Maud Rise, Weddell Sea, Antarctica: College Station, Proceedings of the Ocean Drilling Program, Scientific Results, v. 113, p. 261–315.
- SRINIVASAN, M. S. AND CHATURVEDI, S. N., 1992, Neogene planktonic foraminiferal biochronology of the DSDP Sites along the Ninetyeast Ridge, northern Indian Ocean, in Ishizaki, K. and Saito, T., eds., Centenary of Japanese Micropaleontology: Tokyo, Terra Scientific Publishing Company, p. 175–188.
- SRINIVASAN, M. S. AND KENNEDY, J. P., 1981a, A review of Neogene planktonic foraminiferal biostratigraphy; applications in the Equatorial and South Pacific, in Warmer, J. E., Douglas, R. G., and Winterer, E. L., eds., The Deep

- Sea Drilling Project: A Decade of Progress: Tulsa, Society of Economic Paleontologists and Mineralogists Special Publication 32, p. 395–432.
- SRINIVASAN, M. S. AND KENNEDY, J. P., 1981b, Neogene planktonic foraminiferal biostratigraphy and evolution: equatorial to Subantarctic South Pacific: *Marine Micropaleontology*, v. 6, p. 499–533.
- SRINIVASAN, M. S. AND KENNEDY, J. P., 1983, The Oligocene-Miocene boundary in the South Pacific: *Geological Society of America Bulletin*, v. 94, p. 798–812.
- SRINIVASAN, M. S. AND SINHA, D. K., 1992, Late Neogene planktonic foraminiferal events of the southwest Pacific and Indian Ocean: a comparison, in Tsuchi, R. and Ingle, Jr., J. C., eds., *Pacific Neogene, Environment, Evolution and Events*: Tokyo, University of Tokyo Press, p. 203–220.
- STAINFORTH, R. M., LAMB, J. L., LUTERBACHER, H., BEARD, J. H., AND JEFFORDS, R. M., 1975, Cenozoic planktonic foraminifera zonation and characteristics of index forms: Lawrence, University of Kansas Paleontological Contributions 62, p. 1–425 (in two parts).
- STEININGER, F. F., 1994, Proposal for the Global Stratotype Section and Point (GSSP) for the Base of the Neogene (the Palaeogene/Neogene boundary), International Commission on Stratigraphy, Subcommission on Neogene Stratigraphy; Working Group on the Palaeogene/Neogene Boundary: Vienna, Institute for Paleontology, University of Vienna, 41 p.
- STEININGER, F. F., BERGGREN, W. A., KENT, D. V., BERNOR, R. C., SEN, S., AND AGUSTI, J., 1995, Circum Mediterranean (Miocene and Pliocene) marine-continental chronologic correlations of European mammal units and zones, in Bernor, R. L., Fahlbusch, V., and Rietschel, S., eds., *Later Neogene European Biotic and Stratigraphic Correlation*: New York, Columbia University Press (in press).
- STEINMETZ, J. C. AND STRADNER, H., 1984, Cenozoic calcareous nannofossils from Deep Sea Drilling Project leg 75, southeast Atlantic Ocean: Washington, D.C., Initial Reports of the Deep Sea Drilling Project, v. 75, p. 671–753.
- STOTT, L. D. AND KENNEDY, J. P., 1990, Antarctic Paleogene planktonic foraminifer biostratigraphy: ODP Leg 113, Sites 689 and 690: College Station, Proceedings of the Ocean Drilling Program, Scientific Results, v. 113, p. 549–569.
- SWISHER, C. C., III, DEPAOLO, D., AND OWNES, T., 1994, Age of the Fish Canyon Tuff Sanidine (FCTS): A single crystal $^{40}\text{Ar}/^{39}\text{Ar}$ dating standard (abs.): Berkeley, Eighth International Conference on Geochronology, Cosmochronology and Isotope Geology, United States Geological Survey Circular 1107, p. 312.
- SWISHER, C. C., DINGUS, L., AND BUTLER, R. F., 1993, $^{40}\text{Ar}/^{39}\text{Ar}$ dating and magnetostratigraphic correlation of the terrestrial Cretaceous-Paleogene boundary and Puerca Mammal Age, Hell Creek-Tullock formations, eastern Montana: *Canadian Journal of Earth Sciences*, v. 30, p. 1981–1996.
- SWISHER, C. C., DINGUS, L., MONTANARI, A., AND SMIT, J., 1995, Terminal Cretaceous events in classic marine and terrestrial sections synchronous with Chicxulub impact: *Geophysical Research Letters*, in press.
- SWISHER, C. C., III, GRAJALES-NISHIMURA, J. M., MONTANARI, A., CEDILLO-PARDO, E., MARGOLIS, S. V., CLAEYS, P., ALVAREZ, W., SMIT, J., RENNE, P., MAURASSE, F. J.-M. R., AND CURTIS, G. H., 1992, Chicxulub crater melt-rock and K-T boundary tektites from Mexico and Haiti yield coeval $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 65 Ma: *Science*, v. 257, p. 954–958.
- SWISHER, C. C., III, AND KNOX, R. O'B., 1991, The age of the Paleocene/Eocene boundary: $^{40}\text{Ar}/^{39}\text{Ar}$ dating of the lower part of NP10, North Sea Basin and Denmark (abs): IGCP 308 (Paleocene/Eocene boundary events), International Annual Meeting and Field Conference, 2–6 December 1991, Brussels, Abstracts with Program, p. 16.
- SWISHER, C. C., III, AND PROTHERO, D. R., 1990, Single-crystal $^{40}\text{Ar}/^{39}\text{Ar}$ dating of the Eocene-Oligocene transition in North America: *Science*, v. 249, p. 760–762.
- TAKAYAMA, T., 1993, Notes on Neogene calcareous nannofossil biostratigraphy of the Ontong-Java Plateau and size variations of *Reticulofenestra* coccoliths: College Station, Proceedings of the Ocean Drilling Program, Scientific Results, v. 130, p. 179–229.
- TALWANI, M., WINDISCH, C. C., AND LANGSETH, M. G., 1971, Rekjanes Ridge crest: A detailed geophysical study: *Journal of Geophysical Research*, v. 76, p. 473–517.
- TAUXE, L., DEINO, A., BEHRENSMEYER, A., AND POTTS, R., 1992, Pinning down the Brunhes/Matayama and upper Jaramillo boundaries: a reconciliation of orbital and isotopic time scales: *Earth and Planetary Science Letters*, v. 109, p. 561–572.
- TAUXE, L., GEE, Y., PICK, T., AND BOWN, T., 1994, Magnetostratigraphy of the Willwood Formation, Bighorn Basin, Wyoming: New constraints on the location of the Paleocene/Eocene boundary: *Earth and Planetary Science Letters*, v. 125, p. 159–172.
- TAUXE, L., TUCKER, P., PETERSEN, N. P., AND LAABRECQUE, J. L., 1983, The magnetostratigraphy of Leg 73 sediments: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 42, p. 65–90.
- THEYER, F. AND HAMMOND, S. R., 1974, Cenozoic magnetic time scale in deep-sea cores: completion of the Neogene: *Geology*, v. 2, p. 487–512.
- THOMAS, E., BARRERA, E., HAMILTON, N., HUBER, B. T., KENNEDY, J. P., O'CONNELL, S. B., POSPICHAL, J. J., SPIESS, V., STOTT, L. D., WEI, W., AND WISE, S. W., JR., 1990, Upper Cretaceous-Paleogene stratigraphy of Sites 689 and 690, Maud Rise (Antarctica): College Station, Proceedings of the Ocean Drilling Program, Scientific Results, v. 113, p. 901–914.
- THUNELL, R., 1981, Late Miocene-early Pliocene planktonic foraminiferal biostratigraphy and paleoceanography of low-latitude marine sequences: *Marine Micropaleontology*, v. 6, p. 71–90.
- TOUMARKINE, M., 1981, Discussion de la validité de l'espèce *Hantkenina aragonensis* Nuttall, 1930. Description de *Hantkenina nuttalli* n.sp.: Cahiers de Micropaléontologie, Livre Jubilaire en l'honneur de Madame Y. Le Calvez, fasc. 4, p. 109–119.
- TOUMARKINE, M., AND LUTERBACHER, H., 1985, Paleocene and Eocene planktonic foraminifera, in Bolli, H. M., Saunders, J. B., and Perch-Nielsen, K., *Plankton Stratigraphy*: Cambridge, Cambridge University Press, p. 87–154.
- TOWNSEND, H. A., 1985, The paleomagnetism of sediments acquired from the Goban Spur on Deep Sea Drilling Project 80: Washington, D.C., Initial Reports of the Deep Sea Drilling Project, v. 80, p. 389–421.
- TSUCHI, R., 1984, Neogene biostratigraphy and chronology of Japan, in Ikebe, N. and Tsuchi, R., eds., *Pacific Neogene Datum Planes: Contributions to Biostratigraphy and Chronology*: Tokyo, University of Tokyo Press, p. 223–233.
- TSUCHI, R., TAKAYANAGI, Y., AND SHIBATA, K., 1981, Neogene bio-events in the Japanese islands, in Tsuchi, R., ed., *Neogene of Japan — Its Biostratigraphy and Chronology*: Shizuoka, Faculty of Science, IGCP-114 National Working Group of Japan, p. 15–32.
- TURRIN, B. D., DONNELLY-NOLAW, J. M., AND HEARN, B. C., 1994, $^{40}\text{Ar}/^{39}\text{Ar}$ ages from the rhyolite of Alder Creek, California: Age of the Cobb Mountain normal polarity Subchron revised: *Geology*, v. 22, p. 251–254.
- VAI, G. B., VILLA, I. M., AND COLALONGO, M. L., 1993, First direct radiometric dating of the Tortonian/Messinian boundary: *Comptes Rendus de l' Académie des Sciences de Paris*, t. 316, sér. II, p. 1407–1414.
- VAN COUVERING, J. A. AND BERGGREN, W. A., 1977, Biostratigraphical basis of the Neogene time scale, in Kauffman, E. G. and Hazel, J. E., eds., *Concepts and Methods in Biostratigraphy*: Stroudsburg, Dowden, Hutchinson and Ross, p. 283–306.
- VERHALLEN, P. J. J. M. AND ROMEIN, A. J. T., 1983, Calcareous nannofossils from the Priabonian stratotype and correlation with the parastratotypes, in Setiawan J. R., ed., *Foraminifera and microfacies of the type-Priabonian: Utrecht Micropaleontological Bulletin*, v. 29, p. 163–173.
- VERVLOET, C. C., 1966, Stratigraphical and Micropaleontological Data on the Tertiary of Southern Piemont (northern Italy): Utrecht, Scotanus and Jens, 88 p.
- VON ALIS, K., 1984, Miocene calcareous nannofossil biostratigraphy of Deep Sea Drilling Project Hole 521A (Southeast Atlantic): Washington, D.C., Initial Reports of the Deep Sea Drilling Project, v. 73, p. 425–427.
- WALTER, R. C., MANEGA, P. C., HAY, R. L., DRAKE, R. E., AND CURTIS, G. H., 1991, Laser-fusion $^{40}\text{Ar}/^{39}\text{Ar}$ dating of Bed 1, Olduvai Gorge, Tanzania: *Nature*, v. 354, p. 145–149.
- WEAVER, P. P. E. AND CLEMENT, B. M., 1986, Synchronicity of Pliocene planktonic foraminiferal datums in the North Atlantic: *Marine Micropaleontology*, v. 10, p. 295–307.
- WEAVER, P. P. E. AND CLEMENT, B. M., 1987, Magnetobiostratigraphy of planktonic foraminiferal datums: Deep Sea Drilling Project Leg 94, North Atlantic: Washington, D.C., Initial Reports of the Deep Sea Drilling Project, v. 94, p. 815–829.
- WEI, K. Y., 1987, Tempo and mode of evolution in Neogene planktonic foraminifera: taxonomic and morphometric evidence: Unpublished Ph.D. Dissertation, University of Rhode Island, Kingston, 397 p.
- WEI, W., 1991, Middle Eocene-lower Miocene calcareous nannofossil magnetobiochronology of ODP Holes 699A and 703A in the Subantarctic South Atlantic: *Marine Micropaleontology*, v. 18, p. 143–165.
- WEI, W., 1992, Paleogene chronology of Southern Ocean drill holes: An update, in Kennet, J. P. and Warnke, D. A., eds., *The Antarctic Paleoenvironment: A Perspective on Global Change*: Washington, D.C., American Geophysical Union, Antarctic Research Series, v. 56, p. 75–96.

- WEI, W. 1995, Revised age calibration points for the geomagnetic polarity time scale: *Geophysical Research Letters*, v. 22, p. 159–172.
- WEI, W. AND PELEO-ALAMPAY, A., 1993, Updated Cenozoic nannofossil magnetobiochronology: *INA Newsletter*, v. 15, p. 15–17.
- WEI, W. AND POSPICHAL, J. J., 1991, Danian calcareous nannofossil succession at Site 738 in the southern Indian Ocean: College Station, *Proceedings of the Ocean Drilling Program, Scientific Results*, v. 119, p. 495–512.
- WEI, W. AND THIERSTEIN, H. P., 1991, Upper Cretaceous and Cenozoic calcareous nannofossils of the Kerguelan Plateau (southern Indian Ocean) and Prydz Bay (East Antarctica): College Station, *Proceedings of the Ocean Drilling Program, Scientific Results*, v. 119, p. 467–493.
- WEI, W., VILLA, G., WISE, S. W., JR., 1992, Paleoceanographic implications of Eocene-Oligocene calcareous nannofossils from Sites 711–748 in the Indian Ocean: College Station, *Proceedings of the Ocean Drilling Program, Scientific Results*, v. 120, p. 979–999.
- WEI, W. AND WISE, S. W., 1989, Paleogene calcareous nannofossil magnetobiochronology: Results from South Atlantic DSDP Site 516: *Marine Micropaleontology*, v. 14, p. 119–152.
- WEI, W. AND WISE, S. W., 1990, Middle Eocene to Pleistocene calcareous nannofossils recovered by Ocean Drilling Program Leg 113 in the Weddell Sea: College Station, *Proceedings of the Ocean Drilling Program, Initial Reports*, v. 113, p. 639–666.
- WEI, W. AND WISE, S. W., 1992, Eocene-Oligocene calcareous nannofossil magnetobiochronology of the southern Ocean: *Newsletter in Stratigraphy*, v. 26, p. 119–132.
- WESTERCAMP, D. AND ANDREIEFF, P., 1983, Saint-Barthélemy et ses îlets, Antilles françaises: stratigraphie et évolution magmato-structurelle: *Bulletin Société Géologique France*, v. 25, p. 873–883.
- WILSON, D. S., 1993, Confirmation of the astronomical calibration of the magnetic polarity timescale from sea-floor spreading rates: *Nature*, v. 364, p. 788–790.
- WING, S. L., BROWN, T. M., AND OBRADOVICH, J. D., 1991, Early Eocene biotic and climatic change in interior western North America: *Geology*, v. 19, p. 1189–1192.
- WRIGHT, J. D. AND MILLER, K. G., 1992, Miocene stable isotope stratigraphy, Site 747, Kerguelan Plateau: College Station, *Proceedings of the Ocean Drilling Program, Scientific Results*, v. 120, p. 855–866.
- YANSHIN, L., ed., 1960, *Paleogenovye otlozheniya yuga evropeiskoi yasti SSSR*: Moscow, Izdatel'stvo Akademii Nauk SSSR, 312 p.
- YOUNG, J. R., FLORES, J.-A., WEI, W., AND CONTRIBUTORS, 1994, A summary chart of Neogene nannofossil magnetobiostratigraphy: *Journal of Nannoplankton Research*, v. 16, p. 21–27.
- ZHANG, J., MILLER, K. G., AND BERGGREN, W. A., 1993, Neogene planktonic foraminiferal biostratigraphy of the northeastern Gulf of Mexico: *Micropaleontology*, v. 39, p. 299–326.