Cenozoic geochronology

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ABSTRACT

We present a revised Cenozoic geochronology based upon a best-fit to selected high-temperature radiometric dates on a number of identified magnetic polarity chrons (within the Late Cretaceous, Paleogene, and Neogene) which minimizes apparent accelerations in sea-floor spreading. An assessment of >200 first-order correlations of calcareous plankton biostratigraphic datum events to magnetic polarity stratigraphy yields an improved correlation of the standard magnetostratigraphic, standard biostratigraphic (zonal) and chronostratigraphic boundaries, as well as improved resolution in marine-continental stratigraphic correlations. The time scale presented here has been accepted by the Committee on Geochronology as the standard time scale for the Cenozoic for the Decade of North American Geology (DNAG).

INTRODUCTION

In the more than 20 yr since Funnell (1964) prepared the first relatively precise Cenozoic time scale on the basis of an assessment of biostratigraphically controlled radiometric dates, a series of attempts has been made to further refine Cenozoic geochronology and to integrate this chronology with the magnetostratigraphic and sea-floor spreading record of reversals of geomagnetic polarity (for example, Berggren, 1969, 1972; Opdyke and others, 1974; Theyer and Hammond, 1974; Tarling and Mitchell, 1976).

Several types of general approaches in the construction of a Cenozoic geochronology can be recognized. An emphasis on radiometric dates to determine numerical ages of geologic subdivision boundaries can be referred to as radiochronology; a good recent example of such an approach can be found in Odin and others (1982). Fossils are, however, more abundant than are datable horizons in Phanerozoic sediments. Biochronology is the organization of geologic time according to the irreversible process of biotic evolution and provides an ordinal framework which can measure all but the youngest Phanerozoic time with greater resolution, if with less accuracy, than can radiochronology. The Paleogene time scale of Hardenbol and Berggren (1978) emphasizes this approach. Finally, magnetochronology is based on the characteristic binary sequence of normal

and reversed polarity of the geomagnetic field. It is also ordinal in nature, has a time resolution comparable to biochronology, but is applicable, globally, in a variety of recording media, thus offering a framework in which to relate events on land and in the oceans. The paleomagnetic signal is iterative (that is, it is not unique), and thus a derived chronology is possible only after calibration with a numeric scale based on radiometric dates. Classic examples of magnetochronology are the radiometrically dated reversal time scale for 0–4 Ma (Cox and others, 1963; McDougall and Tarling, 1963; Cox, 1969; Dalrymple, 1972) and the 0–80-Ma geomagnetic polarity time scale deduced from sea-floor spreading magnetic anomalies by extrapolation (Heirtzler and others, 1968).

Recent advances in magnetobiostratigraphic studies, particularly on exposed marine deposits in the Mediterranean region (Lowrie and others, 1982), epicontinental deposits in northwest Europe (Townsend, 1982; Aubry, 1983), and deep-sea sediments recovered by the DSDP hydraulic piston core (Poore and others, 1982, 1983) have resulted in direct correlation between plankton biostratigraphy and magnetic polarity stratigraphy for the entire Cenozoic. The geochronology of this era thus requires a full integration of biochronologic, magnetochronologic, and radiochronologic approaches in the construction of an internally consistent time scale; the time scales of Ryan and others (1974) for the Neogene and Lowrie and Alvarez (1981) for the Paleogene illustrate such an integrated methodology. We summarize here a magnetobiochronology for the Cenozoic that incorporates available magnetobiostratigraphic correlations for both marine and nonmarine sections, as well as much needed age-calibration data in the middle Cenozoic from radiometrically dated polarity stratigraphy.

TABLE 1. LATE CRETACEOUS AND CENOZOIC AGE-CALIBRATION DATA
FOR MAGNETIC REVERSAL SEQUENCE

| Calibration level	Age (Ma)	Reference
Gauss/Gilbert (Anomaly 2A)	3.40	Mankinen and Dalrymple, 1979
Younger end of Anomaly 5	8.87	Evans, 1970; Harrison and others, 1979
Younger end of Anomaly 12	32.4	Prothero and others, 1982
Younger end of Anomaly 13	34.6	Prothero and others, 1982
Younger end of Anomaly 21	49.5	Flynn, 1981
Santonian/Campanian boundary (younger end of Anomaly 34)	84.0	Lowrie and Alvarez, 1977; Obradovich and Cobban, 1975

Note: see Berggren and others (1985a, 1985b) for additional details.

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GEOMAGNETIC POLARITY TIME SCALE

The geomagnetic reversal time scale is based on the radiometrically dated magnetic polarity data set on lavas for 0 to 4 Ma (Mankinen and Dalrymple, 1979) and extended in time by age calibration of the polarity sequence inferred from marine magnetic anomalies. The polarity sequence compiled by LaBrecque and others (1977) is taken as representative of the sea-floor spreading record for the Late Cretaceous and Cenozoic. (Although Cenozoic chronology is our central interest here, the apparent continuity of the marine magnetic anomaly record requires that the ridge-crest sequence be considered in its entirety in the development of a revised magnetochronology to avoid the introduction of discontinuities.) In order to satisfy six selected high-temperature, age-calibration tie-points (Table 1) and to minimize apparent accelerations in sea-floor–spreading history, we consider this polarity sequence as three linear segments on a calibration age versus apparent age (related to distance) plot (Fig. 1). An initial segment is defined by the origin, a 3.40-Ma radiometric age for the Gauss/Gilbert boundary and an 8.87-Ma age for the younger boundary of Anomaly 5, yielding an extrapolated age of 10.42 Ma for the older boundary of Anomaly 5. Available radiometric age estimates for magnetozones in land sections correlated to the younger boundaries of Anomalies 12, 13, and 21 (32.4, 34.6, and 49.5 Ma, respectively) are used to extend the chronology by a linear best fit anchored to the estimated age for the older boundary of Anomaly 5; an estimated age of 56.14 Ma for the older boundary of Anomaly 24 is extrapolated from this segment. Interpolation between this estimated age for anomaly 24 and a radiometric age of 84 Ma for Anomaly 34 (based on correlation of the magnetozone equivalent with the Campanian/Santonian boundary) completes the reversal chronology
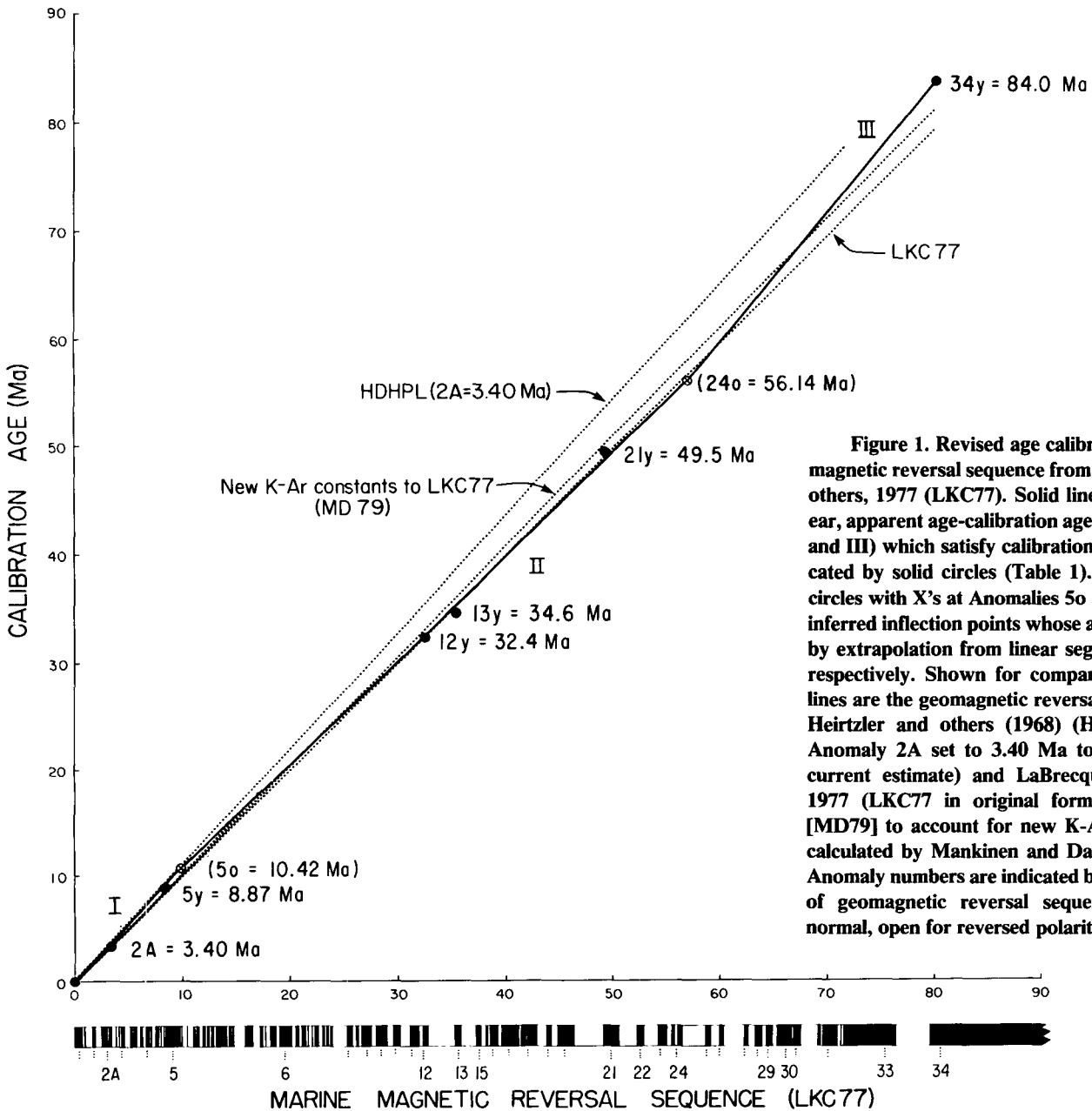
Figure 1. Revised age calibration of marine magnetic reversal sequence from LaBrecque and others, 1977 (LKC77). Solid lines are three linear, apparent age-calibration age segments (I, II, and III) which satisfy calibration tie-points indicated by solid circles (Table 1). The two open circles with X's at Anomalies 5o and 24o are the inferred inflection points whose ages are derived by extrapolation from linear segments I and II, respectively. Shown for comparison by dotted lines are the geomagnetic reversal time scales of Heirtzler and others (1968) (HDHPL68 with Anomaly 2A set to 3.40 Ma to conform with current estimate) and LaBrecque and others, 1977 (LKC77 in original form and modified [MD79] to account for new K-Ar constants as calculated by Mankinen and Dalrymple, 1979). Anomaly numbers are indicated below bar graph of geomagnetic reversal sequence (filled for normal, open for reversed polarity).

to the younger end of the Cretaceous Long Normal Polarity Interval, corresponding to the oceanic Cretaceous Quiet Zones.

Ages for magnetic polarity intervals (Table 2) are calculated according to the linear regression equations of these three time segments. Relative precision of the reversal sequence depends on the spatial resolution of the magnetic anomaly data and the assumption that sea-floor spreading occurred on some ridge system at a constant rate over tens of millions of years. The accuracy of the reversal chronology ultimately depends on the radiometric age data set used for calibration and the method of interpolation. Remarkably, the first extended magnetochronology proposed by Heirtzler and others (1968), which was based on a simple extrapolation from Anomaly 2A for a South Atlantic profile, gives age estimates for magnetochrons that are within 10% of the absolute age estimates summarized here. This agreement indicates that the constant spreading-rate assumption applied to selected areas of the world ocean is a very good first-order approximation in the derivation of a geomagnetic reversal chronology.

COMPARISON TO BIOCHRONOLOGY

Cenozoic chronology and chronostratigraphy is drawn directly from Berggren and others (1985a, 1985b). Integrated biostratigraphy and magnetostratigraphy in some European Paleogene and Neogene stratotype sections and an assessment of ~200 Cenozoic and Late Cretaceous calcareous plankton datum events directly correlated with magnetic polarity stratigraphy in deep-sea sediment cores and land sections provide improved identification of the boundaries and durations of chronostratigraphic units in terms of planktonic biostratigraphy and magnetic polarity chrons.

Our assessment of published radiometric dates suggests the following best biochronologic age estimates for Cenozoic Epoch boundaries: Pliocene/Pleistocene: <2 Ma; Miocene/Pliocene: ~5 Ma; Oligocene/Miocene: ~23.5 Ma; Eocene/Oligocene: ~37 Ma; Paleocene/Eocene: ~56.5 Ma; Cretaceous/Tertiary: ~66 Ma. The radiometric data on which these age estimates are based, especially in the Paleogene, are biased toward those obtained from high-temperature minerals; age estimates based on radiometric dates from glauconites tend to be younger, particularly in the Paleogene (for example, Odin and others, 1982).

Our biochronological age estimates show good agreement with the revised magnetochronologic age estimates. The largest discrepancy is at the Paleocene/Eocene boundary for which an assessment of biostratigraphically controlled radiometric dates on high-temperature minerals suggests an age of 56.5 Ma, which is ~1 m.y. younger than the biostratigraphically controlled magnetochronologic age estimate of 57.8 Ma. Respective biochronological and magnetochronological age estimates for the Eocene/Oligocene boundary (37 Ma and 36.6 Ma) differ in the opposite sense by 0.4 m.y.; those for the Oligocene/Miocene boundary (23.5 Ma and 23.7 Ma) are in substantial agreement. A magnetochronologic age estimate of 66.4 Ma for the Cretaceous/Tertiary boundary also agrees well with the estimate of 66.5 Ma obtained from dates (recalculated to ICC constants) in Obradovich and Cobban (1975). For subdivision of the Neogene, age estimates are typically already based on magnetochronologic criteria (for example, Ryan and others, 1974), and a comparison of biochronologies and magnetochronologies is therefore not very meaningful. Available biostratigraphically or magnetostratigraphically controlled radiometric dates are very consistent with our magnetochronologic age estimates, however, being without systematic deviation (Berggren and others, 1985b).

Biochronologic age estimates used as calibration tie-points in the geomagnetic reversal time scale of Lowrie and Alvarez (1981) agree rea-

TABLE 2. REVISED GEOMAGNETIC POLARITY TIME SCALE FOR CENOZOIC AND LATE CRETACEOUS TIME

Normal polarity interval (Ma)	Anomaly	Normal polarity interval (Ma)	Anomaly
0.00-0.73	1	24.04-24.21	6C
0.91-0.98		25.50-25.60	7
1.66-1.88	2	25.67-25.97	7
2.47-2.92	2A	26.38-26.56	7A
2.99-3.08	2A	26.86-26.93	8
3.18-3.40	2A	27.01-27.74	8
3.88-3.97	3	28.15-28.74	9
4.10-4.24	3	28.80-29.21	9
4.40-4.47	3	29.73-30.03	10
4.57-4.77	3	30.09-30.33	10
5.35-5.53	3A	31.23-31.58	11
5.68-5.89	3A	31.64-32.06	11
6.37-6.50		32.46-32.90	12
6.70-6.78	4	35.29-35.47	13
6.85-7.28	4	35.54-35.87	13
7.35-7.41	4	37.24-37.46	15
7.90-8.21	4A	37.48-37.68	15
8.41-8.50	4A	38.10-38.34	16
8.71-8.80		38.50-38.79	16
8.92-10.42	5	38.83-39.24	16
10.54-10.59		39.53-40.43	17
11.03-11.09		40.50-40.70	17
11.55-11.73	5A	40.77-41.11	17
11.86-12.12	5A	41.29-41.73	18
12.46-12.49		41.80-42.23	18
12.58-12.62		42.30-42.73	18
12.83-13.01	5AA	43.60-44.06	19
13.20-13.46	5AB	44.66-46.17	20
13.69-14.08	5AC	48.75-50.34	21
14.20-14.66	5AD	51.95-52.62	22
14.87-14.96	5B	53.88-54.03	23
15.13-15.27	5B	54.09-54.70	23
16.22-16.52	5C	55.14-55.37	24
16.56-16.73	5C	55.66-56.14	24
16.80-16.98	5C	58.64-59.24	25
17.57-17.90	5D	60.21-60.75	26
18.12-18.14	5D	63.03-63.54	27
18.56-19.09	5E	64.29-65.12	28
19.35-20.45	6	65.50-66.17	29
20.88-21.16	6A	66.74-68.42	30
21.38-21.71	6A	68.52-69.40	31
21.90-22.06	6AA	71.37-71.65	32
22.25-22.35	6AA	71.91-73.55	32
22.57-22.97	6B	73.96-74.01	
23.27-23.44	6C	74.30-80.17	33
23.55-23.79	6C	84.00-118.00	34

TABLE 3. BOUNDARY AGE ESTIMATES AND DURATIONS FOR INFORMAL SUBDIVISIONS OF THE CENOZOIC

Epoch	Time (Ma)	Duration (m.y.)	Remarks
Pleistocene	1.6-0	1.6	
Pliocene	5.3- 1.6	3.7	
Late	3.4- 1.6	1.8	
Early	5.3- 3.4	1.9	
Miocene	23.7- 5.3	18.4	
Late	10.4- 5.3	5.1	
Middle	16.5-10.4	6.1	
Early	23.7-16.5	7.2	
Ogligocene	36.6-23.7	12.9	
Late	30.6-23.7	6.3	
Early	36.6-30.0	6.6	
Eocene	57.8-36.6	21.2	Note major change in duration
Late	40.0-36.6	3.4	of Eocene (~21 m.y.) at the
Middle	52.0-40.0	12.0	expense of the Paleocene
Early	57.8-52.0	5.8	(~9 m.y.). Indeed, the Eocene is the longest of the Cenozoic Epochs.
Paleocene	66.4-57.8	8.6	
Late	62.3-57.8	4.5	
Early	66.4-62.3	4.1	

Note: criteria for the recognition of these and other subdivisions and their correlation to the magnetic reversal sequence are discussed fully in Berggren and others (1985a, 1985b).
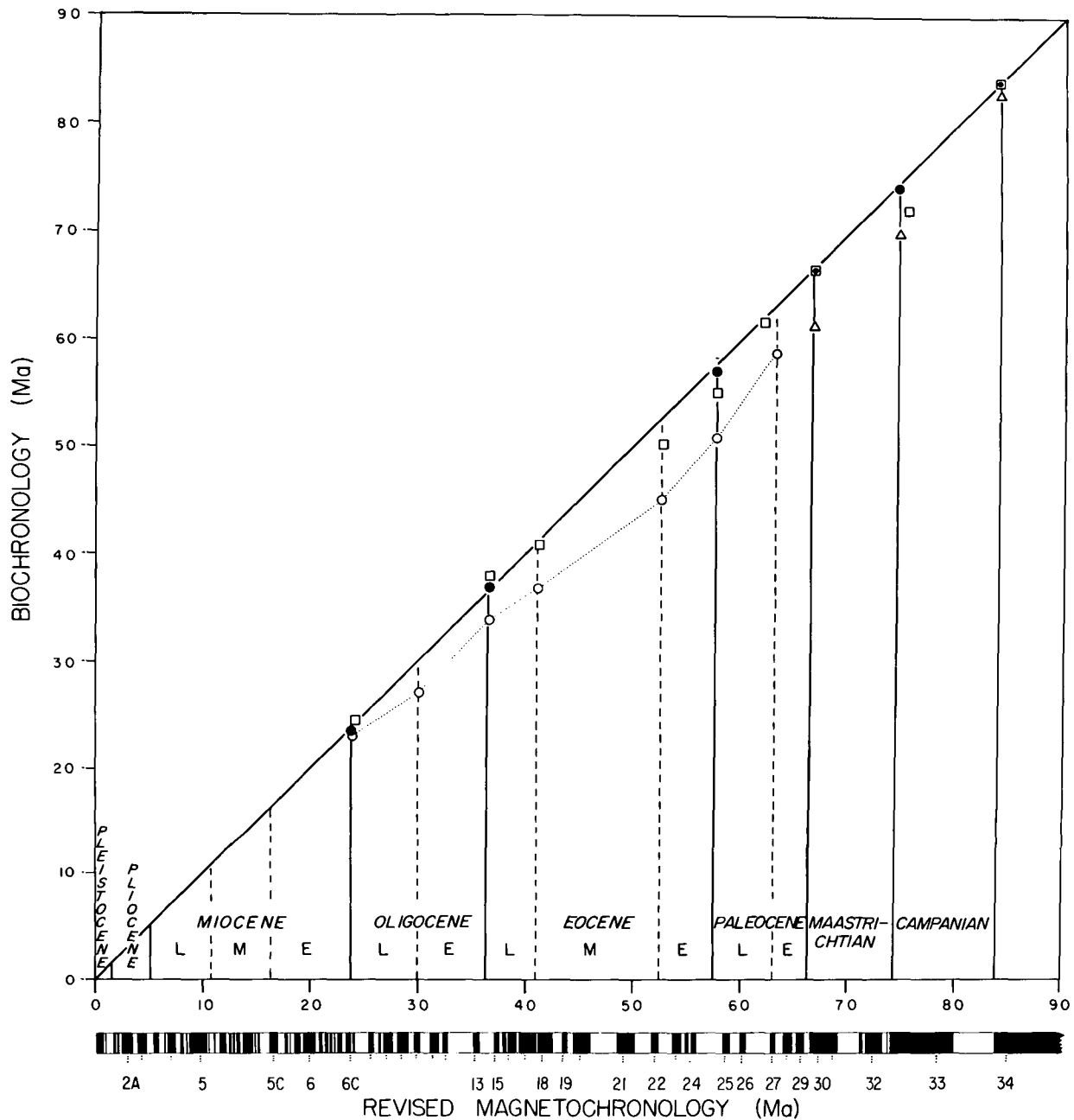
Figure 2. Comparison of various biochronological estimates of Paleogene epoch and intra-epoch boundaries within magnetochronological framework provided by correlation to revised geomagnetic polarity time scale. Solid circles: this paper. Open circles: from Odin and Curry (1981). Squares: recalculated from Hardenbol and Berggren (1978) by Ness and others (1980) and used for calibration of geomagnetic reversal sequence by Lowrie and Alvarez (1981). Open triangle: from Owens and Sohl (1973). Anomaly numbers are indicated below bar graph of geomagnetic reversal sequence (filled for normal, open for reversed polarity).

sonably well with the biochronology and magnetochronology presented here, with the exception of the early Eocene (Fig. 2). This difference (2 to 3 m.y.), however, may be more apparent than real, because the age estimates from Hardenbol and Berggren (1978) used by Lowrie and Alvarez via Ness and others (1980) for the Paleogene are now superceded by those of Berggren and others (1985a).

Systematic and significant departures from our preferred age esti-

mates are evident in the chronology for the Paleogene, based mainly on K-Ar dates on glauconites from northwest Europe (Odin and others, 1982). Numerical differences range up to ~7 m.y. (in the early Eocene), the glauconite ages being invariably younger than are our age estimates, which preferentially include K-Ar dates on igneous rocks (Fig. 2). The specific cause of this difference in age estimates remains to be resolved, but because glauconite is not widely regarded as a very reliable chronometer
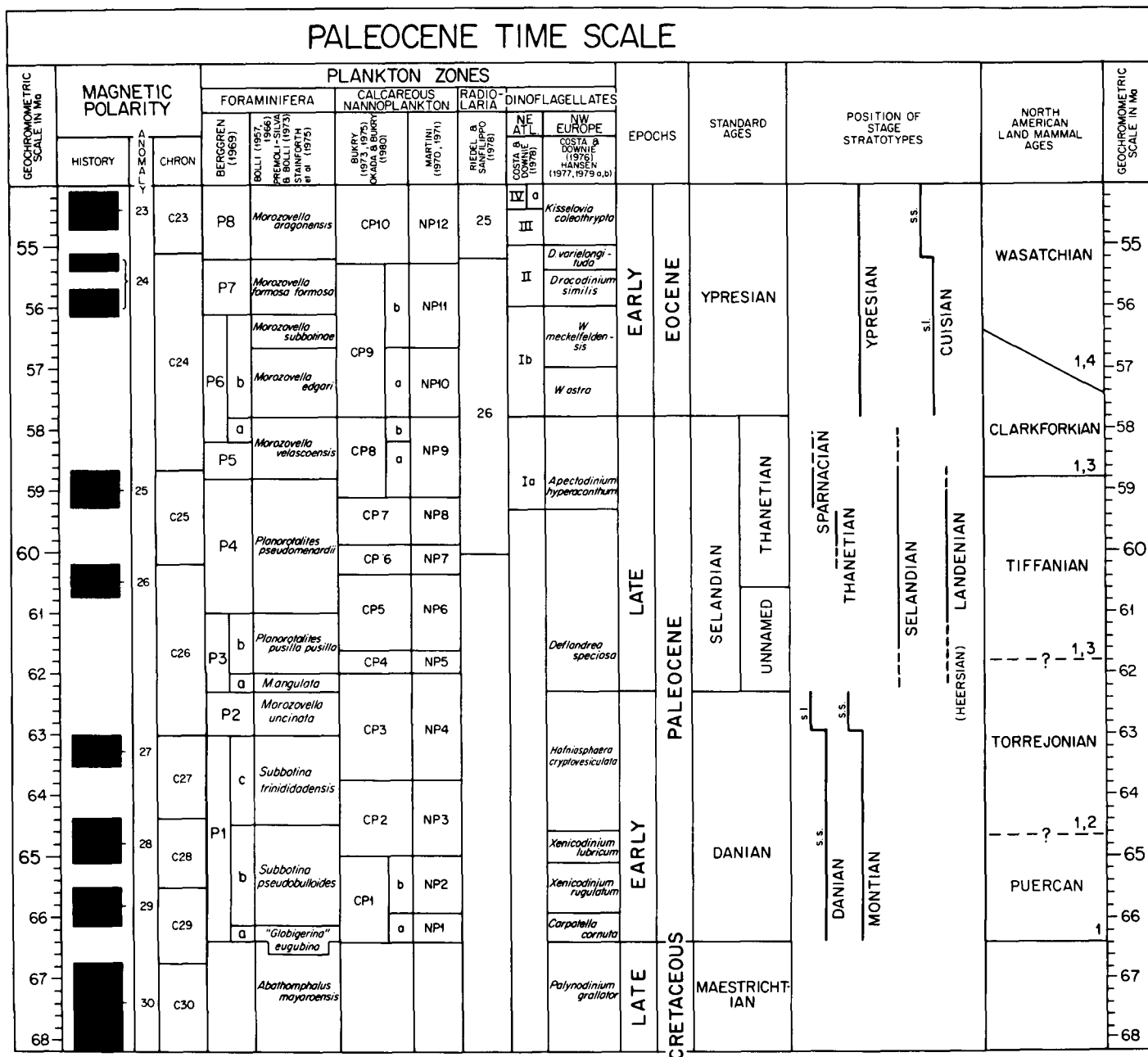
Figure 3. Paleocene geochronology. The geochronologic scale is from Figure 1. The position of the zonal boundaries is based, for the most part, upon direct (first-order) correlation between biostratigraphic datum levels and paleomagnetic polarity stratigraphy as determined in deep-sea cores or continental marine sediments. The extent (duration) of standard time-stratigraphic units and their boundaries and the position of stage stratotypes are estimated on the basis of their relationship to standard plankton biostratigraphic zones. Magnetobiochronology of Paleocene North American land-mammal ages is shown on the right (footnote numbers at boundaries refer to sources used in determining the temporal position of these boundaries). Explanation of sources denoted by footnote numbers: (1) This paper—based on data and discussions presented in the text. (2) Adapted from Tomida and Butler, 1980; Tomida, 1981. (3) Butler and others, 1981a, 1981b; Rapp and others, 1983. (4) Butler and others, 1981a, 1981b; Rapp and others, 1983; Rose, 1980; Gingerich, 1976, 1980. (5) Radiometric dates and discussion in West and others, in press. (6) Flynn, 1981, 1983a, 1983b. (7) Radiometric dates in Black, 1969; McDowell and others, 1973. (8) Prothero and others, 1982, 1983 (supported by radiometric dates near the base of the Arikareean, R. H. Tedford, 1982, personal commun.). (9) Radiometric dates in McDowell and others, 1973; Wilson, 1980.

EOCENE TIME SCALE

GEOCHRONOMETRIC SCALE IN Ma	MAGNETIC POLARITY			PLANKTON ZONES							EPOCHS	STANDARD AGES	POSITION OF STAGE STRATOTYPES	NORTH AMERICAN MAMMAL AGES	GEOCHRONOMETRIC SCALE IN Ma
	HISTORY	ANOMALY	CHRON	FORAMINIFERA 1	FORAMINIFERA 2	CALCAREOUS NANNOPLANKTON 3	CALCAREOUS NANNOPLANKTON 4	RADIO-LARIA 5	DINOFLAGELLATE NE ATL 6	DINOFLAGELLATE NW EUROPE 7					

Magnetic Polarity Chrons (top to bottom): C12, C13, C15, C16, C17, C18, C19, C20, C21, C22, C23, C24, C25

Anomalies: 13, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25

Foraminifera zones:
- P18 — Cassig chipolensis-Pseudoh. micra
- P17
- P16 — Gr cerroazulensis
- P15 — Port semiinvoluta (1969, 1979)
- P14 — Truncorotaloides rohri
- P13 — Orbulinoides beckmanni
- P12 — Morozovella lehneri
- P11 — Globigerapsis subconglobata
- P10 — Hantkenina aragonensis
- P9 — Acarinina pentacamerata
- P8 — Morozovella aragonensis
- P7 — Morozovella formosa formosa
- P6 b — Morozovella subbotinae / Morozovella edgari
- P6 a
- P5 — Morozovella velascoensis
- P4

Calcareous Nannoplankton (col 3): CP16, CP15, CP14, CP13, CP12, CP11, CP10, CP9, CP8, CP7, CP6

Calcareous Nannoplankton (col 4): NP21, NP19/20, NP18, NP17, NP16, NP15, NP14, NP13, NP12, NP11, NP10, NP9, NP8, NP7

Radiolaria (col 5): 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26

Dinoflagellate NE Atl (col 6): VI, V, IV, III, II, Ib, Ia

Dinoflagellate NW Europe (col 7):
- Wetzeliella gochtii
- Rhombodinium perforatum
- Gochtodinium simplex
- Rhombodinium porosum
- Rhombodinium draco
- W articulata
- Kisselovia coleothrypta rotundata
- Kisselovia fasciata
- Kisselovia coleothrypta
- D varielongituda
- Dracodinium similis
- W meckelfeldensis
- W astra
- Apectodinium hyperacanthum
- DEFLANDREA SPECIOSA

Epochs:
- OLIGOCENE — EARLY
- EOCENE — LATE / MIDDLE / EARLY
- PALEOCENE — LATE

Standard Ages: RUPELIAN, PRIABONIAN, BARTONIAN, LUTETIAN, YPRESIAN, SELANDIAN

Position of stage stratotypes: RUPELIAN, TONGRIAN, PRIABONIAN, BARTONIAN, LUTETIAN, YPRESIAN s.s., CUISIAN s.l., SELANDIAN, THANETIAN, SPARNACIAN

North American Mammal Ages: STAMPIAN, CHADRONIAN, DUCHESNEAN, UINTAN, BRIDGERIAN, WASATCHIAN, CLARKFORKIAN, TIFFANIAN

Mammal age reference numbers: 1,8,9; 5,7; 1,5,6; 1,5; 1,4; 1,3

Geochronometric scale (Ma): 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60

RADIOLARIAN ZONES

16 *Thyrsocyrtis bromia*
    c) *Cryptoprora ornata*
    b) *Calocyclas bandyca*
    a) *Carpocanistrum azyx*
17. *Podocyrtis goetheana*
18. *Podocyrtis chalara*
19. *Podocyrtis mitra*
20. *Podocyrtis ampla*
21. *Thyrsocyrtis triacantha*
22. *Theocampe mongolfieri*
23. *Theocotyle cryptocephala*
24. *Phormocyrtis*
25. *Buryella clinata*
26. *Bekoma bidartensis*

PLANKTON ZONES

1. *Berggren (1969)*
   Blow (1979)

2. *Bolli (1957, 1966)*
   Premoli - Silva
   & Bolli (1973)
   Staninforth et al
   (1975)

3. *Bukry (1973,1975)*
   Okada & Bukry (1980)

4. *Martini (1970,1971)*

5. *Riedel & Sanfilippo*
   (1978)

6. *Costa & Downie*
   (1979)

7. *Costa & Downie*
   (1976)
   Bujak (1979)
   Bujak et al. (1980)
   Chateauneuf & Gruas-
   Cavagnetto (1978)

Figure 4. Eocene geochronology (explanation as in Fig. 3).

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(for example, Obradovich and Cobban, 1975), the systematically younger glauconite dates are strongly suspected to be anomalous (Berggren and others, 1985a).

It is clear that incorporation of our preferred biochronological age estimates for Cenozoic boundaries as calibration data would result in a magnetochronology that is virtually the same as the one we derived from a more restricted age data set (Table 1) which is less directly dependent on biochronology. The high internal consistency of this integrated magneto-biochronology supports the use of the age-calibrated magnetic reversal

sequence as a vernier (analogous to the use of age-calibrated stratigraphic thickness) to obtain precise age estimates for various boundaries, in accordance with magnetobiostratigraphic correlations. In effect, the philosophy and approach of the Ryan and others time scale (1974) is extended to the Paleogene. Numerical ages in the Cenozoic geologic time scale shown in Figures 3–6 are therefore based on the revised magnetochronology summarized above. Numerical age estimates for Cenozoic Epoch boundaries (and their informal subdivisions) are shown in Table 3.

DISCUSSION

Features of interest in this revised Cenozoic time scale include the following.

1. The fact that Paleogene-stage stratotypes are unconformity-bounded and related to eustatic sea-level changes makes precise biostratigraphic recognition of the boundaries difficult. A comparison of the magnetobiostratigraphic record across some of these unconformity-bounded boundaries suggests that, as a first estimate, the eustatic sea-level cycle (regression-transgression) was on the order of 1–3 m.y. If the concept that "base defines stage" is rigorously maintained, it may prove more efficacious to redefine the base of the Cenozoic stages *within* the normal marine cycles, allowing easier biostratigraphic recognition and correlation. This would have the effect of making the boundaries younger than currently determined by most stratigraphers, including the boundary positions shown here (Figs. 3–6). Alternatively, new stratotype sections could be sought in continuous deep-water (bathyal) marine sequences.

2. The Cretaceous/Tertiary boundary is biostratigraphically linked in marine sequences with a level within Chron C29R (chron terminology for the Paleogene after LaBrecque and others, 1983). In terrestrial sequences, this boundary has been linked with a level within Chron C28N or Chron C28R; however, the interpretation of the latter data is somewhat ambiguous, and we await further studies to clarify whether the two boundaries are, in fact, of different ages or, as we suspect, actually coeval (within Chron C29R).

3. The type Danian is biostratigraphically linked with the Chron C28 and younger half of Chron C29 interval and may extend into the older half of the Chron C27 interval. There is a substantial stratigraphic gap between the top of the Danian s.s. (within Chron C27) or top of the Danian s.l. (= Montian s.s.) (= younger end of Chron C27) and the base of the Thanetian (= mid-Chron C26N), an interval of ~3 and 2 m.y., respectively. The Thanetian thus would appear to be inappropriate as a time-stratigraphic unit for the entire post-Danian, pre-Ypresian Paleocene. Recent biostratigraphic studies suggest that the Selandian is a more appropriate unit for this stratigraphic interval (see Berggren and others, 1985a). Alternatively, the Selandian stage could be subdivided into a lower (as yet unnamed) substage and an upper (Thanetian) substage.

4. The lower (early) Eocene has undergone substantial revision in this study. Biostratigraphic studies show that the Ypresian/Lutetian boundary is biostratigraphically linked with a level at, or slightly younger than, the NP13/NP14 boundary which is associated with the older end of Chron C22N, whereas the First Appearance Datum (FAD) of *Hantkenina*, nominate taxon of Zone P10, and which has commonly been used by planktonic foraminiferal biostratigraphers to denote the base of the Lutetian, is associated with the youngest part of Chron C22N (see Berggren and others, 1985a). The temporal difference between these two biostratigraphic levels is on the order of 1 m.y. The eustatic sea-level fall (and corresponding unconformity which is seen between the Ypresian and Lutetian stages and at correlative levels in various sections) occurs within Zones NP13 and P9, and the regressive-transgressive cycle associated with this event is probably, to a first approximation, on the order of 2–3 m.y. in the northwest European stratotype sections (Aubry, 1983). Revised age

Figure 5. Oligocene geochronology (explanation as in Fig. 3).

estimates for the early Eocene are 52.0–57.8 Ma (compare with previous estimates of 49–53.5 Ma; Hardenbol and Berggren, 1978). The age estimate on the early/middle Eocene boundary (52 Ma) is consistent with the recent assignment of radiometrically dated levels (~49 Ma) near the Bridgerian-Uintan "land-mammal age" boundary which has been correlated to the reversed polarity interval of Chron C20R (Berggren and others, 1985a).

5. The precise correlation of the middle/late Eocene boundary with the magnetic polarity stratigraphic scale remains somewhat equivocal. Common biostratigraphic criteria include the FAD *Porticulasphaera semiinvoluta* (top Chron C18), Last Appearance Datum (LAD) *Morozovella-Acarinina* group (mid-Chron C17), FAD *Chiasmolithus oamaruensis* and/or LAD *Chiasmolithus grandis* (= later part of Chron C18 or later part of Chron C17). We have chosen to place the middle/late Eocene boundary in the later part of Chron C17 with an estimated age of 40.0 Ma.

6. The recent integration of high-temperature K-Ar dates and magnetic polarity stratigraphy on latest Eocene–early Oligocene land-mammal ages in North America (Prothero and others, 1982, 1983) has placed new constraints on age estimates of the Eocene/Oligocene boundary and on magnetochrons C12 and C13. Chron C12 is associated with three K-Ar biotite dates of 32.4 Ma, 33.5 Ma, and 34.6 Ma in stratigraphic superposition. These dates support an age estimate of the Eocene/Oligocene boundary (correlated to Chron C13R) of ~36–37 Ma (Berggren and others, 1985a). The Eocene/Oligocene boundary is biostratigraphically linked (LAD *Globorotalia cerroazulensis-cocoaensis* group, LAD *Hantkenina*, slightly above the LAD of rosette-shaped discoasters, *D. saipanensis, D. barbadiensis*), having a level approximately midway between the limits of Chron C13, with an estimated age of 36.6 Ma. This age estimate is consistent with several (predominantly glauconitic) dates of ~37 Ma, biostratigraphically associated with the boundary in the Gulf Coast and in northwest Europe. It is inconsistent with other (predominantly glauconitic) dates from northwest Europe and from fission-track dates on mikrotektites from the North American strewn field(s). We view these latter dates as anomalously young. Alternatively, the dates on the strewn fields may be reliable, and the problem may rather be one of correlation to the Eocene/Oligocene boundary.

7. The Oligocene is best served by a two-fold time-stratigraphic subdivision: Rupelian (lower) and Chattian (upper). The boundary between these two stages is biostratigraphically linked with the LAD of *Chiloguembelina* and the NP23/NP24 boundary, which are associated with Chron C10 with an estimated age of 30 Ma. Previous correlations which linked the Rupelian/Chattian boundary (Chron C10) with the LAD of *Pseudohastigerina* (midway between the limits of Chron C13, ~34 Ma) are incorrect (Hardenbol and Berggren, 1978).

8. Numerous biostratigraphic criteria have been suggested to determine the position of the Oligocene/Miocene boundary. We have chosen the FAD of *Globorotalia kugleri* and the LAD of *Reticulofenestra bisecta* (associated with mid-C6CN) as definitive criteria. The resulting magnetochronologic age estimate (23.7 Ma) is in close agreement with recent assessments of published radiometric dates which suggest an age of 23–24 Ma for the Oligocene/Miocene boundary. The genus *Globigerinoides* appears sporadically as early as Chron C7 (~26 Ma) but attains numerical prominence in deep-sea faunas only in the latest Oligocene (in the reversed interval, just older than Chron C6CN; according to previous Neogene magnetostratigraphic chron terminology of Theyer and Hammond, 1974; Opdyke and others, 1974). It thus retains its usefulness as a guide to the approximate position of the Oligocene/Miocene boundary.

9. Although the age estimates of the upper and lower boundaries of the Paleogene made here do not differ significantly from those made earlier, major differences are seen within the Eocene. The Eocene (~21 m.y.) has expanded chronologically at the expense of the Paleocene (~9

m.y.) and is, in fact, the longest of the Cenozoic epochs. Indeed, the middle Eocene (Lutetian and Bartonian; late Chron C22 to approximately the Chron C17/C18 boundary) is ~11–12 m.y. long, longer than the entire Paleocene.

10. The FAD of *Orbulina* occurs in Anomaly 5B correlative (Chron C5BN), with an estimated magnetochronologic age estimate of 15.2 Ma, in precise agreement with a recent assessment of radiometric dates that places the same numerical value on this datum level.

11. The "*Hipparion* datum," which defines the base of the Vallesian Land Mammal Age, has been dated at 12.5 Ma and is therefore correlated to mid-Serravallian (= Chron C5AR). Magnetostratigraphic studies in the Siwaliks of Pakistan show, however, that the first hipparions in the Indian subcontinent were associated with the early part of Chron C5N, which was previously estimated to be ~9.5 Ma (Barry and others, 1982; Tauxe and Opdyke, 1982). Our revision, which would bring this level to ~10 Ma, does not resolve the inconsistency, but recent reviews of the morphology of hipparions show that two "datum events" are involved. Collateral descendants of North American *Cormohipparion* arrived first at ~12.5 Ma in temperate Eurasia and North Africa ("*primigenium*" or "facial-fossa Type 1" group), and a second lineage entered India at 10 Ma.
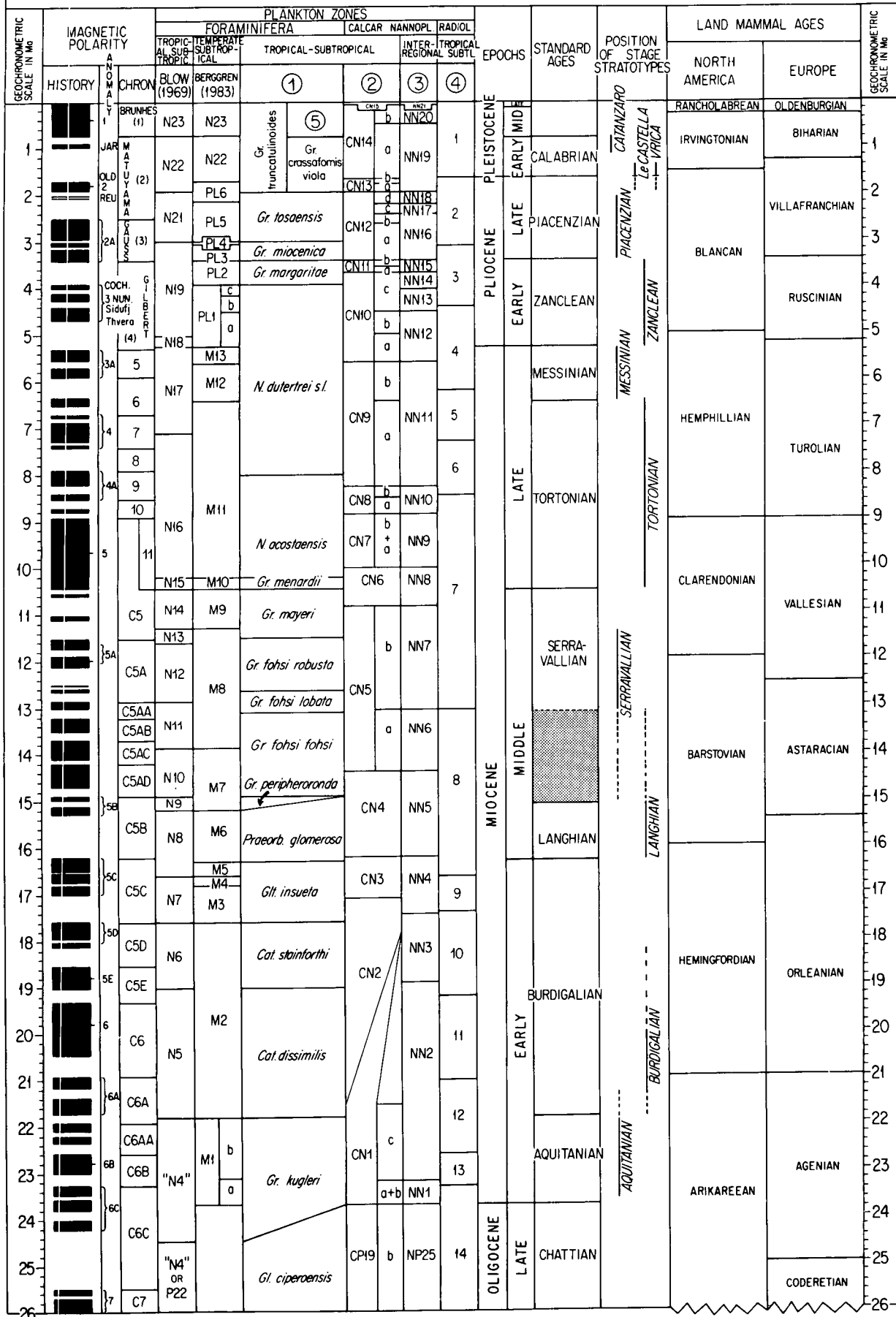
12. In a recent paper on the magnetostratigraphy and K-Ar geochronology of basalts in northwest Iceland, McDougall and others (1984) reported an estimate of 11.1 Ma for the age of the older boundary of marine magnetic Anomaly 5. The study of Tauxe and others (1984, in press), however, on the magnetostratigraphy of the middle Miocene Ngorora Formation in the East African Rift Valley of Kenya, combined with K-Ar age dates on intraformational tuff beds, supports a much younger age for this boundary, ~10 Ma. The age of 10.42 Ma which we derive for the older boundary of Anomaly 5 by extrapolation of sea-floor spreading rates therefore lies at about the average numerical value of these recent radiometrically derived estimates. As Tauxe and others (in press) concluded from this disparity, isotopic ages can have errors far greater than quoted analytical uncertainties, limiting temporal correlation using radiochronology alone to a resolution of perhaps only 10% of the age. Much better temporal resolution, if not accuracy, is obtained using a combination of magnetochronology, biochronology, and radiochronology.

13. The Miocene part of the revised paleomagnetic time scale differs significantly from previous versions. It has become apparent from recently available magnetobiostratigraphic data that the correlation of Chron 9 = Chron C5N (Theyer and Hammond, 1974; Ryan and others, 1974) cannot be easily accommodated. The original correlation (Chron 11 = Chron C5N; Foster and Opdyke, 1970) is preferable. The magnetobiostratigraphic arguments supporting this change are discussed in greater detail in Berggren and others, 1985b). The realignment of calcareous plankton zones (and corresponding correlations with siliceous plankton zones) to magnetic anomaly correlatives results in an ~1.5- to 2-m.y. shift (toward younger age estimates) over part of the middle and late Miocene interval.

14. The Pliocene-Pleistocene part of the revised Neogene paleomagnetic time scale remains essentially unchanged from earlier versions. The Miocene/Pliocene boundary and the Pliocene/Pleistocene boundary are placed, respectively, in the basal part of the Gilbert Chron (5.3 Ma) and just above the Olduvai Normal Subchron (1.6 Ma).

15. In view of our proposed realignment of the magnetostratigraphically defined chrons, with respect to the chrons derived from marine magnetic anomaly identification in the Miocene, and the strong possibility for confusion that this presents, we suggest that future magnetostratigraphic correlations be made directly to the well-developed marine magnetic anomaly expression of geomagnetic reversals. Accordingly, the chron terminology for the early and middle Miocene shown in Figure 6 follows the nomenclature of Cox (1982), with the addition of the prefix "C," which is then consistent with Paleogene chron terminology of LaBrecque and oth-
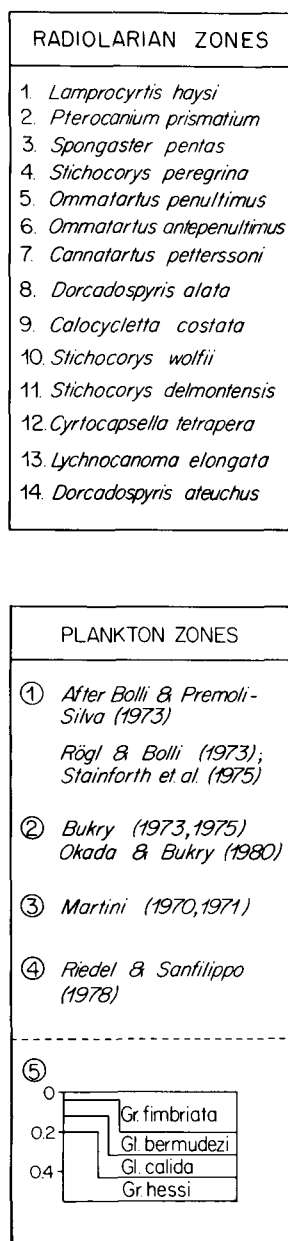
NEOGENE TIME SCALE

GEOCHRONOMETRIC SCALE IN Ma	MAGNETIC POLARITY			PLANKTON ZONES							EPOCHS	STANDARD AGES	POSITION OF STAGE STRATOTYPES	LAND MAMMAL AGES		GEOCHRONOMETRIC SCALE IN Ma
				FORAMINIFERA			CALCAR NANNOPL.		RADIOL					NORTH AMERICA	EUROPE	
	HISTORY	ANOMALY	CHRON	TROPICAL-SUBTROPICAL BLOW (1969)	TEMPERATE-SUBTROPICAL BERGGREN (1983)	TROPICAL-SUBTROPICAL ①	②	INTER-REGIONAL ③	TROPICAL SUBTL ④							

Magnetic Polarity / Chron column (top to bottom):
BRUNHES (1), JAR, OLD 2 REU (MATUYAMA) (2), (2A) GAUSS (3), COCH. 3 NUN. Sidufj Thvera GILBERT (4), 3A 5, 6, 4 7, 8, 4A 9, 10, 5 11, C5 N14, N13, 5A C5A, C5AA, C5AB, C5AC, C5AD, 5B C5B, 5C C5C, 5D C5D, 5E C5E, 6 C6, 6A C6A, C6AA, 6B C6B, 6C C6C, "N4" OR P22, 7 C7

Foraminifera BLOW (1969): N23, N22, N21, N19, N18, N17, N16, N15, N14, N13, N12, N11, N10, N9, N8, N7, N6, N5, "N4"

Foraminifera BERGGREN (1983): N23, N22, PL6, PL5, PL4, PL3, PL2, PL1, M13, M12, M11, M10, M9, M8, M7, M6, M5, M4, M3, M2, M1

Foraminifera ① (zones): Gr. truncatulinoides ⑤, Gr. crassafomis viola, Gr. tosaensis, Gr. miocenica, Gr. margaritae, N. dutertrei s.l., N. acostaensis, Gr. menardii, Gr. mayeri, Gr. fohsi robusta, Gr. fohsi lobata, Gr. fohsi fohsi, Gr. peripheroronda, Praeorb. glomerosa, Glt. insueta, Cat. stainforthi, Cat. dissimilis, Gr. kugleri, Gl. ciperoensis

Calcareous Nannoplankton ②: CN14, CN13, CN12, CN11, CN10, CN9, CN8, CN7, CN6, CN5, CN4, CN3, CN2, CN1, CP19

Nannoplankton ③: NN20, NN19, NN18, NN17, NN16, NN15, NN14, NN13, NN12, NN11, NN10, NN9, NN8, NN7, NN6, NN5, NN4, NN3, NN2, NN1, NP25

Radiolaria ④: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14

EPOCHS: PLEISTOCENE, PLIOCENE, MIOCENE (LATE, MIDDLE, EARLY), OLIGOCENE (LATE)

STANDARD AGES: CALABRIAN, PIACENZIAN, ZANCLEAN, MESSINIAN, TORTONIAN, SERRA-VALLIAN, LANGHIAN, BURDIGALIAN, AQUITANIAN, CHATTIAN

POSITION OF STAGE STRATOTYPES: CATANZARO, Le CASTELLA — VRICA, PIACENZIAN, ZANCLEAN, MESSINIAN, TORTONIAN, SERRAVALLIAN, LANGHIAN, BURDIGALIAN, AQUITANIAN

LAND MAMMAL AGES — NORTH AMERICA: RANCHOLABREAN, IRVINGTONIAN, BLANCAN, HEMPHILLIAN, CLARENDONIAN, BARSTOVIAN, HEMINGFORDIAN, ARIKAREEAN

LAND MAMMAL AGES — EUROPE: OLDENBURGIAN, BIHARIAN, VILLAFRANCHIAN, RUSCINIAN, TUROLIAN, VALLESIAN, ASTARACIAN, ORLEANIAN, AGENIAN, CODERETIAN

RADIOLARIAN ZONES

1. Lamprocyrtis haysi
2. Pterocanium prismatium
3. Spongaster pentas
4. Stichocorys peregrina
5. Ommatartus penultimus
6. Ommatartus antepenultimus
7. Cannatartus pettersoni
8. Dorcadospyris alata
9. Calocycletta costata
10. Stichocorys wolfii
11. Stichocorys delmontensis
12. Cyrtocapsella tetrapera
13. Lychnocanoma elongata
14. Dorcadospyris ateuchus

PLANKTON ZONES

① After Bolli & Premoli-
   Silva (1973)

   Rögl & Bolli (1973);
   Stainforth et al. (1975)

② Bukry (1973,1975)
   Okada & Bukry (1980)

③ Martini (1970,1971)

④ Riedel & Sanfilippo
   (1978)

⑤
   0   ┌─────────────┐
            │ Gr. fimbriata
   0.2   │ Gl. bermudezi
            │ Gl. calida
   0.4   │ Gr. hessi
            └─────────────┘

Figure 6. Neogene geochronlogy (explanation as in Fig. 3).

ers (1983) already in use. The magnetostratigraphic chrons (including the names for the four most recent chrons) are, however, indicated for mainly historical reasons and to emphasize the proposed realignment of these chrons in the late Miocene; magnetic anomaly chron subdivisions for the late Miocene to Recent can be found in Cox (1982).

CONCLUSION

The Cenozoic magnetobiochronology presented here is consistent with much of the available high-temperature K-Ar dates and some of the low-temperature (glauconite) dates. Notable discrepancies with the latter are noted in the early part of the Paleogene, particularly the Eocene. The

revised geochronology presented here differs from other time scales in the following respects.

1. The magnetochronologic framework is based exclusively on high-temperature, K-Ar age-calibration points associated with magnetic polarity intervals which can be correlated to the standard geomagnetic polarity sequence derived from marine magnetic anomalies.

2. Direct, first-order correlations are made between calcareous plankton biostratigraphic datum levels and magnetic stratigraphy for the entire spectrum of the Cenozoic.

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