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The Neogene: Part 2

Neogene geochronology and chronostratigraphy

W. A. Berggren, D. V. Kent and J. A. van Couvering

SUMMARY: We present a revised Neogene 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 first order correlations of calcareous plankton biostratigraphic datum events to magnetic polarity stratigraphy yields the following estimated magnetobiochronology of major chronostratigraphic boundaries: Oligocene/Miocene (Chron C6CN): 23.7 Ma; Miocene/Pliocene (slightly younger than Gilbert/Chron 5 boundary): 5.3 Ma; Pliocene/Pleistocene (slightly younger than Olduvai Subchron): 1.6 Ma.

Changes to the marine time-scale are relatively minor in terms of recent and current usage except in the interval of the middle Miocene where new DSDP data reveal that previous correlations of magnetic anomalies 5 and 5A to magnetic polarity Chrons 9 and 11, respectively, are incorrect. Our revised magnetobiostratigraphic correlations result in a 1.5–2 m.y. shift towards younger magnetobiochronologic age estimate in the middle Miocene. Radiometric dates correlated to bio- and magnetostratigraphy in continental section generally support the revised marine magnetobiochronology presented here. Major changes, however, are made in marine–non-marine correlations in the Miocene in Eurasia which indicate African–Eurasian migrations through the Persian Gulf as early as 20 Ma. The 12.5 Ma estimate of the *Hipparion* datum is supported by recent taxonomic revisions of the hipparions and magnetobiostratigraphic correlations which show that primitive hipparions first arrived in Eurasia and North Africa at c.12.5 Ma and a second wave in the tropics (i.e. Indian and central Africa) at c.10 Ma.

Neogene geochronology and chronostratigraphy:

The large issues in Neogene biostratigraphy and geochronology have been the subject of a number of papers during the past decade (*i. al.*, Berggren 1971, 1972, 1973, 1981; Berggren & Van Couvering 1974, 1978; Van Couvering & Berggren 1977; Ryan *et al.* 1974; Steininger 1977; Steininger *et al.* 1976; Steininger & Papp 1979; Ikebe *et al.* 1972, 1977; Tsuchi, (ed.) 1981). The common thread connecting these papers is the effort to continually improve upon Neogene chronology through an evaluation and integration of new data, predominantly from the fields of planktonic biostratigraphy, magnetostratigraphy and radiochronology. Recently, in a paper prepared for the International Workshop on Pacific Neogene Biostratigraphy by IGCP Project 114 (Biostratigraphic Datum Planes of the Pacific Neogene), one of the authors (Berggren 1982) reviewed the status of Neogene geochronology, placing particular emphasis on the various methodologies used in constructing magnetostratigraphic chronologies and the constraints placed upon alternate schemes by palaeobiologically controlled radiochronology.

Even in the short time since that review was completed, a considerable amount of new data has become available from magneto-biostratigraphic studies on Hydraulic Piston Cores (HPCs) taken by the Glomar Challenger, primarily in the North and South Atlantic; and also from integrated radiochronologic and magnetobiostratigraphic studies on mid-Tertiary terrestrial deposits. The magnetostratigraphic identification of several radiometrically dated mid-Tertiary terrestrial beds has provided us with much needed calibration points for the formulation of an improved Cenozoic time-

scale (Prothero *et al.* 1982).

In this paper we shall outline the methodology used in devising a new, improved Cenozoic time-scale and then present a general discussion of the magnetobiochronology of Neogene chronostratigraphy. A detailed discussion of Neogene chronostratigraphic units will not be presented here; interested readers may find this information presented in adequate detail in Berggren (1971), Berggren & Van Couvering (1974), Van Couvering & Berggren (1977), and Ryan *et al.* (1974).

Neogene magnetostratigraphy

As for many other geological phenomena, our knowledge of geomagnetic polarity reversals is better known for the most recent times, in this case encompassing the Neogene. After confirmation of geomagnetic reversals and the development of a magnetic polarity time-scale for about the past 4 Ma using measurements on discrete lava flows, it has been possible to extend the record of geomagnetic reversals further back in time by extrapolation using various methods and assumptions. Magnetostratigraphic investigation of sedimentary and volcanic sequences and analysis of marine magnetic anomalies over active sea-floor spreading ridge systems have provided abundant, mutually supportive evidence for geomagnetic polarity reversal history. In the process, the chronostratigraphy of the Cenozoic, particularly the Neogene, has been intricately tied to the development and use of the polarity time-scale.

The first precise knowledge of geomagnetic reversal history was obtained from the radiometric-age distribution of basaltic lavas of normal (in the same sense as the present day field)

and reversed polarity (Cox *et al.* 1963; 1964). It was soon established that geomagnetic reversals do not occur regularly but define polarity intervals with durations ranging from about 50 ky to over 1000 ky (Cox 1969). The irregularity in polarity duration seems to be a characteristic feature of geomagnetic reversals, providing a signature which allows a reversal sequence to be correlated and identified. Normal and reversed polarity intervals have no intrinsic properties that allow them to be distinguished from intervals of like polarity; only the relative lengths of polarity intervals are diagnostic for their identification. Thus reference to the time-scale of geomagnetic reversals should be considered in an ordinal sense. Only when the geomagnetic reversal sequence is tied to the cardinal geological time-scale does it achieve its great potential in chronostratigraphy.

The current status of the geomagnetic reversal time-scale derived from radiometrically-dated lavas has been reviewed recently by Mankinen & Dalrymple (1979). In the perspective of geological time, the transition from one polarity state to another occupies an instant, on the order of 5 ky, and is globally synchronous. Because of inherent analytical errors in radiometric age determinations, typically a few percent in this time range, there are inconsistencies in the age-polarity distribution around what is supposed to reflect a simple transition from one polarity state to another. For example, a basalt with normal polarity may have a radiometric date that falls within an age population having predominantly reversed polarity. A statistic has been devised (Cox & Dalrymple 1967) to determine the best age estimate of a polarity reversal, wherein these inconsistencies are minimized by assuming that they are due to dating errors and not to additional reversals within a relatively small time window. This technique has been applied to estimate the ages of major subdivisions, now referred to as chrons (Anonymous 1979), in the youngest part of the polarity time-scale. According to Mankinen & Dalrymple (1979) the best estimates (using revised K-Ar decay constants) for chrons in the interval 0–4 Ma are:

Brunhes/Matuyama:	0.73 Ma
Matuyama/Gauss:	2.47 Ma
Gauss/Gilbert:	3.40 Ma

The presence of shorter polarity intervals or subchrons within these chrons is also detected in the radiometric-polarity data set. However, the data are usually neither sufficiently dense nor are the age determinations precise enough to allow good estimates of the age of the reversals that bound the subchrons. An exception reported recently is for the most recent subchron, the Jaramillo, for which radiometric age estimates of 0.91 and 0.98 Ma have been obtained (Mankinen *et al.* 1980).

The inability to resolve subchron units becomes more acute as the age increases beyond about 5 Ma to the extent that even the longer chrons are difficult to resolve. This limitation results from the fact that analytical errors stay relatively constant as a percentage of calculated age and thus represent an increasingly large error in absolute terms farther back in time. Dalrymple *et al.* (1967) have shown that given even an infinite number of radiometric date-polarity data, where the dates have an uncertainty of 3%, the polarity structure beyond about 4 or 5 Ma cannot be constructed with any degree of confidence if the polarity intervals are about 1 Ma and less. This severe limitation stems largely from the total dependence on the age dates to determine both absolute age

and relative age since the basalts are not otherwise physically related or ordered in some sequence.

The refinement of the 0–4 Ma magnetic reversal time-scale and its extension back in time are thus dependent on palaeo-magnetic study of rock units in continuous sequence, either stratigraphic (magnetostratigraphy) or lateral (sea-floor spreading marine magnetic anomalies). The rate of the recording mechanism (i.e. sedimentation or sea-floor spreading) can be determined by correlation to the radiometrically-determined ages of the youngest chrons; ages of other polarity reversals can then be estimated by interpolation or extrapolation.

For several reasons, marine magnetic anomaly data provide the best, most reproducible and extended record of geomagnetic polarity history. A large number of track lines exist which allow detailed cross-correlation of the anomaly signature on a global basis. The continuity and completeness of the marine magnetic anomaly record of reversals is demonstrated by the observation that over all spreading systems, essentially the same anomaly pattern is found, differing primarily by a proportionality constant that reflects formation of oceanic crust at different spreading rates. If segments of reversal history are missing, then global hiatuses in sea-floor spreading are required, interruptions that are also not evident in the sea-floor depth vs. age relationships accounted for by simple cooling models (Parsons & Sclater, 1977).

In contrast, there are relatively few long magnetostratigraphic sections available to allow detailed checks in their completeness and both changes in rates of deposition and hiatuses are not infrequent in sedimentary sequences. The prime use of magnetostratigraphy has been to provide corroborating evidence for reversals and a framework for correlation of biostratigraphic events into the geomagnetic polarity sequence derived from marine magnetic anomaly data. For the Neogene in particular, the magnetic reversal time-scale provides critical information for chronostratigraphy by such correlations.

Magnetostratigraphy

The magnetostratigraphy of late Miocene to Pleistocene* deep-sea sediments has been well documented and is by now well known (Hays *et al.* 1969; Foster & Opdyke 1970; Opdyke 1972; Saito *et al.* 1975). Since this interval overlaps the age range of the radiometric reversal time-scale, age estimates for biostratigraphic and palaeoceanographic events recorded in the sediments can be determined by interpolation rather precisely after correlation of magnetozones to the radiometrically dated magnetochrons. For example, the time-scale for Pliocene–Pleistocene oxygen isotope stratigraphy (Shackleton & Opdyke 1973, 1976, 1977), and the best current age estimate for the Pliocene–Pleistocene boundary (Haq *et al.* 1977) are based largely on magneto-chronology. Age estimates of the Jaramillo Subchron (Opdyke 1969) and the Olduvai Subchron (Opdyke & Foster 1970) have also been obtained using the sedimentary record.

Extension of the magnetostratigraphic record near to the base of the Neogene has been accomplished in conventional piston cores of deep-sea sediments (Foster & Opdyke 1970; Theyer & Hammond 1974a, b; Opdyke *et al.* 1974), providing direct biostratigraphic correlation to magnetozones. In order

* We do not use the term Holocene in the formal sense here, preferring to consider it rather as merely an interglacial period.

to place calcareous plankton biostratigraphy for the entire Neogene into a magnetostratigraphic framework, Ryan *et al.* (1974) used a complex correlation network involving magnetobiostratigraphic data from DSDP sites, conventional piston cores and exposed sedimentary sections. In the process, the European Neogene stages could be correlated to the marine magnetic anomaly sequence. They also recognized that the geomagnetic polarity time-scale, as developed from analysis of the magnetic anomaly signature of reversals, could be used to estimate ages for stage and system boundaries. In effect, they assumed that over appreciable time intervals, sea-floor spreading rates are more apt to be constant than sedimentation rates. Consequently the geomagnetic polarity time-scale should provide an improved basis for linear interpolation between levels of known or inferred age. The validity of these age estimates of course depends upon both the correlation to the geomagnetic polarity time-scale and how well the polarity time-scale is calibrated.

A considerable quantity of additional magnetobiostratigraphic data from both marine and terrestrial sequences have become available since the work of Ryan *et al.* (1974). This information allows further refinements in correlations to the standard geomagnetic polarity sequence and an assessment of these data is presented later in this paper (see also Appendix). The geomagnetic polarity sequence has also received additional attention and several revised versions have appeared. Since the chronology of geomagnetic polarity reversals now has a very direct bearing on Neogene chronostratigraphy, we present a new, revised polarity time-scale that incorporates what we believe are the best available calibration age data. The major differences among various versions of the polarity time-scale occur in the Palaeogene and are discussed in the companion paper by Berggren *et al.* (this volume). An outline of our methodology is presented here with emphasis on the Neogene.

Regarding polarity interval nomenclature, it should be noted that at least three schemes are in effect for the Neogene. Although the four most recent chrons are named after eminent geomagnetic researchers (Brunhes, Matuyama, Gauss, and Gilbert), this system of nomenclature was impractical for earlier chrons due to their large number. Hays & Opdyke (1967) introduced an identification scheme for magnetostratigraphy in which about 1 Ma intervals of predominantly normal or reversed polarity are numbered sequentially from 1 (the Brunhes, although the first four chrons usually retain their familiar names); odd numbers refer to predominantly normal intervals and even numbers reversed polarity intervals. Subchrons are then identified by letter suffixes added to the chron number. Opdyke *et al.* (1974) and Theyer & Hammond (1974a, b) extended this scheme to Chron 23, near the base of the Neogene. This sequential numbering scheme for chrons has not been further extended into the Paleogene. Instead, it has been found most useful to adapt the well-established numbering scheme of marine magnetic anomalies originally introduced in Pitman & Heirtzler (1966) and Heirtzler *et al.* (1968). For example, in the system proposed by LaBrecque *et al.* (1983), a chron is defined as extending from the youngest reversal boundary of a numbered anomaly to the youngest boundary of the next older numbered anomaly; the chron is named for the correlative magnetic anomaly number, with the letter 'C' (for chron) prefixed to avoid confusion with the pre-existing Neogene chron numbering nomenclature. A similar scheme has been also suggested by Cox (1982). Thus

the interval of predominantly normal polarity corresponding to the Gauss Chron (Cox *et al.* 1964) (correlated to marine magnetic anomaly 2A) can be also referred to as Chron 3 (Hays & Opdyke 1967) or as Chron C2AN (LaBrecque *et al.* 1983), where the suffix 'N' refers to the normal polarity interval(s) associated with the magnetic anomaly.

Difficulties arose in attempts to correlate the chron subdivisions (*sensu* Hays & Opdyke 1967) with the standard marine magnetic anomaly sequence, particularly around the interval of Chron 9 and older. Foster & Opdyke (1970) originally correlated Chron 11 with Chron C5N (normal polarity interval represented by magnetic anomaly 5). Theyer & Hammond (1974a) discussed the problem of correlation of the deep-sea core magnetostratigraphy to the marine magnetic reversal sequence. On the basis of a variety of biostratigraphic arguments, they proposed that Chron 9 is instead correlative to chron C5N and this correlation scheme was used by Ryan *et al.* (1974) and in most subsequent Neogene time-scales (Berggren 1974; Van Couvering & Berggren 1977; Berggren & Van Couvering 1978). It has now become apparent from recently available magnetobiostratigraphy that this correlation (Chron 9 = Chron C5N) cannot be easily accommodated and in fact the original correlation (Chron 11 = Chron C5N) is preferable. The magnetobiostratigraphic arguments supporting this change are presented below under the Miocene.

Figure 2 shows our revised magnetostratigraphic chron correlations to the marine magnetic sequence, down only to Chron 11. We have not found it possible to recorrelate the magnetostratigraphic chrons older than Chron 11 to the standard marine magnetic reversal sequence in any convincing manner. An exception is the correlation of anomaly 5B (= C5BN) and Chron 15 owing to the fact that the position of Chron 15 is the same in both of the alternative correlations (anomaly 5 = Chron 9 vs. anomaly 5 = Chron 11) discussed by Theyer & Hammond (1974a: 316, 317). One obstacle is that the magnetostratigraphic chrons were originally correlated (Foster & Opdyke 1970; Theyer & Hammond 1974a; Ryan *et al.* 1974) to the marine magnetic reversal sequence of Heirtzler *et al.* (1968). The magnetic reversal pattern between anomalies 5 and 6 had been subsequently revised substantially (Blakeley 1974) and it is in part the differences between the Heirtzler *et al.* and Blakeley versions in this interval that make the magnetostratigraphic chrons difficult to realign. In any case, the marine magnetic reversal sequence is much better defined than the magnetostratigraphic record and we suggest that future magnetobiostratigraphic correlations go directly to the marine magnetic expression of geomagnetic reversals. Accordingly, we show chron labels for the anomaly 5 correlative and older portion of the Neogene that are based on the marine magnetic nomenclature, following at this level of detail the scheme proposal by Cox (1982). The magnetostratigraphic chrons (including the labels for the four most recent chrons) are retained to Chron 11 for mostly historical reasons and to emphasize the proposed change in correlation to the sea-floor magnetic anomalies. The chron terminology derived from magnetic anomaly nomenclature, however, can be easily obtained because the polarity intervals corresponding to the numbered marine magnetic anomalies are indicated. Note that because of the aperiodic nature of polarity reversals and the different ways in which the polarity intervals were subdivided (i.e. key, easily identifiable magnetic anomalies of positive polarity vs. intervals of about 1 m.y. of predominantly normal or reversed polarity), the

chron boundaries according to the different schemes usually do not coincide. Ramifications and implications of the proposed change in correlations are discussed in the Miocene section of the manuscript.

Revised geomagnetic polarity time-scale

The first extended geomagnetic reversal time-scale was presented by Heirtzler *et al.* (1968) who selected a magnetic profile from the South Atlantic Ocean as representative of geomagnetic reversal history for about the past 80 Ma. Their chronology of reversals, hereafter referred to as HDHPL68, was derived by correlation of the axial anomalies to the radiometrically-dated magnetic reversal time-scale and then by extrapolation to the oldest then recognized anomaly (anomaly 32). This twenty-plus fold extrapolation assumed that the rate of sea-floor spreading in the South Atlantic was constant over 1400 km or 80 Ma, at the rate calculated from the ridge axis (time zero) to anomaly 2A (then dated at 3.35 Ma). Despite this large extrapolation, it is now apparent that HDHPL68 was within about 10% of current age estimates for this reversal sequence, an indication that the assumption of a constant rate of sea-floor spreading over prolonged time intervals is not an unreasonable approximation.

Virtually all subsequent polarity time-scales rely to some degree on the constant spreading rate assumption; differences arise mainly from the assignment and use of additional age-calibration data for interpolation and extrapolation. The apparent continuity of the marine magnetic anomaly record also requires that the entire sequence be considered at the same time in revision of the chronology. This is because changes in one portion of the sequence will tend to propagate to other portions, or else artificial discontinuities may be introduced. Moreover, geologic stage and epoch subdivision do not have, as far as we know, any particular significance with respect to sea-floor spreading history so that it would be both difficult to justify and out of context to attempt a revision only, for example, of the Neogene portion of the Polarity time-scale. However, the magnetic anomaly sequence extending from the present spreading ridge axes is bounded at the older end by the Cretaceous quiet zone, corresponding to a prolonged interval of constant normal polarity containing few if any correlatable reversals. Consequently it is possible and convenient to analyse the late Cretaceous to Recent sequence of magnetic anomalies as a unit.

As a representative sequence of geomagnetic polarity for the late Cretaceous to Pleistocene, we use a slightly modified version of the LaBrecque *et al.* (1977) time-scale (referred to here as LKC77). Several refinements of HDHPL68 are incorporated in LKC77, most importantly for the Neogene, revisions of the polarity reversal pattern between anomalies 5 and 6 (Blakeley 1974) and from the central anomaly to anomaly 3A (Klitgord *et al.* 1975). Virtually the entire Neogene portion of the anomaly signature of geomagnetic reversals has therefore been re-examined in detail, and adjusted accordingly to reflect the best available data. In contrast, the Paleogene portion is still largely based on the relative spacings of anomalies originally determined by Heirtzler *et al.* (1968). A minor modification made to LKC77 is that the polarity interval lengths described by Blakeley (1974) are recalculated according to the original age estimate in HDHPL68 for the younger end of anomaly 5. The result-

ing overall sequence is thus assembled from essentially the same data as in a recent compilation by Ness *et al.* (1980).

Unlike HDHPL68 which was largely based on the relative spacing of magnetic anomalies in a single profile, the present standard sequence reflects an aggregate of several segments, each obtained by averaging over several profiles and from different spreading systems, and is therefore highly unlikely to be observed anywhere in its entirety, with exactly the same relative spacing. (In fact, even LKC77 does not require sea-floor spreading in the South Atlantic at a single constant rate for the entire late Cretaceous to Recent interval.) Thus while it would be preferable conceptually to use a true length unit in describing a standard reversal sequence and to refer to actual rates in discussing the implications of its age calibration, the use of time units as a common denominator is required to express the best estimate of a geomagnetic reversal sequence synthesized from varied sources. Because of the ordinal nature of the magnetic reversal time-scale, the units they are given in can be referred to as apparent time units to facilitate discussion of their recalibration in time.

The age calibration tie-points we use are listed below and plotted with respect to their position in the modified LKC77 reversal sequence in Fig. 1. All ages have been converted where necessary to the new K-Ar radiometric dating system constants using tables in Dalrymple (1979).

(a) 3.40 Ma—Anomaly 2A (Chron C2A) or the Gauss–Gilbert boundary (Mankinen & Dalrymple 1979). Based on an analysis of radiometric date-magnetization polarity determinations on unrelated lavas. This is presently the oldest well-dated reversal in the classical radiometrically-dated reversal time-scale and a traditional calibration point in virtually all Late Cretaceous to Recent geomagnetic reversal time-scales.

(b) 8.87 Ma—Anomaly 5y (younger end of Chron C5 or Chron 11). Based on stratigraphically-controlled distribution of radiometric date-magnetic polarity determinations on lavas from New Zealand and Iceland. Age represents the mean of 8.90 Ma from New Zealand and 8.83 Ma from Iceland (Evans 1970; Harrison *et al.* 1979).

(c) 32.4 Ma—Anomaly 12y (younger end of Chron C12). Based on magnetostratigraphic studies in Oligocene vertebrate-bearing continental beds in the western United States. Radiometric (K-Ar) date on biotite in volcanic ash stratigraphically overlying normal magnetozone correlated to Chron C12 (Prothero *et al.* 1982).

(d) 34.6 Ma—Anomaly 13y (younger end of Chron C13). Same source as item c; radiometric date (K-Ar) on biotite in volcanic ash stratigraphically overlying normal magnetozone correlated to Chron C13 (Prothero *et al.* 1982).

(e) 49.5 Ma—Anomaly 21y (younger end of Chron C21). Based on magnetostratigraphic studies on Eocene continental and marine beds in the western United States. Age interpolated from radiometric (K-Ar) dates on lavas and tuffs stratigraphically bracketing the top of a normal polarity magnetozone correlated to C21 (Flynn 1981).

(f) 84.0 Ma—Anomaly 34y (Chron C34 or the end of Cretaceous Long Normal). Age estimate for Campanian–Santonian boundary by Obradovich & Cobban (1975) on basis of K-Ar dates on bentonites from western interior of North America; the Campanian–Santonian boundary lies very near to the upper part of a normal magnetozone, correlated to Chron C34, in Italian limestones (Lowrie & Alvarez 1977).

The radiometric age estimate for the younger end of Chron

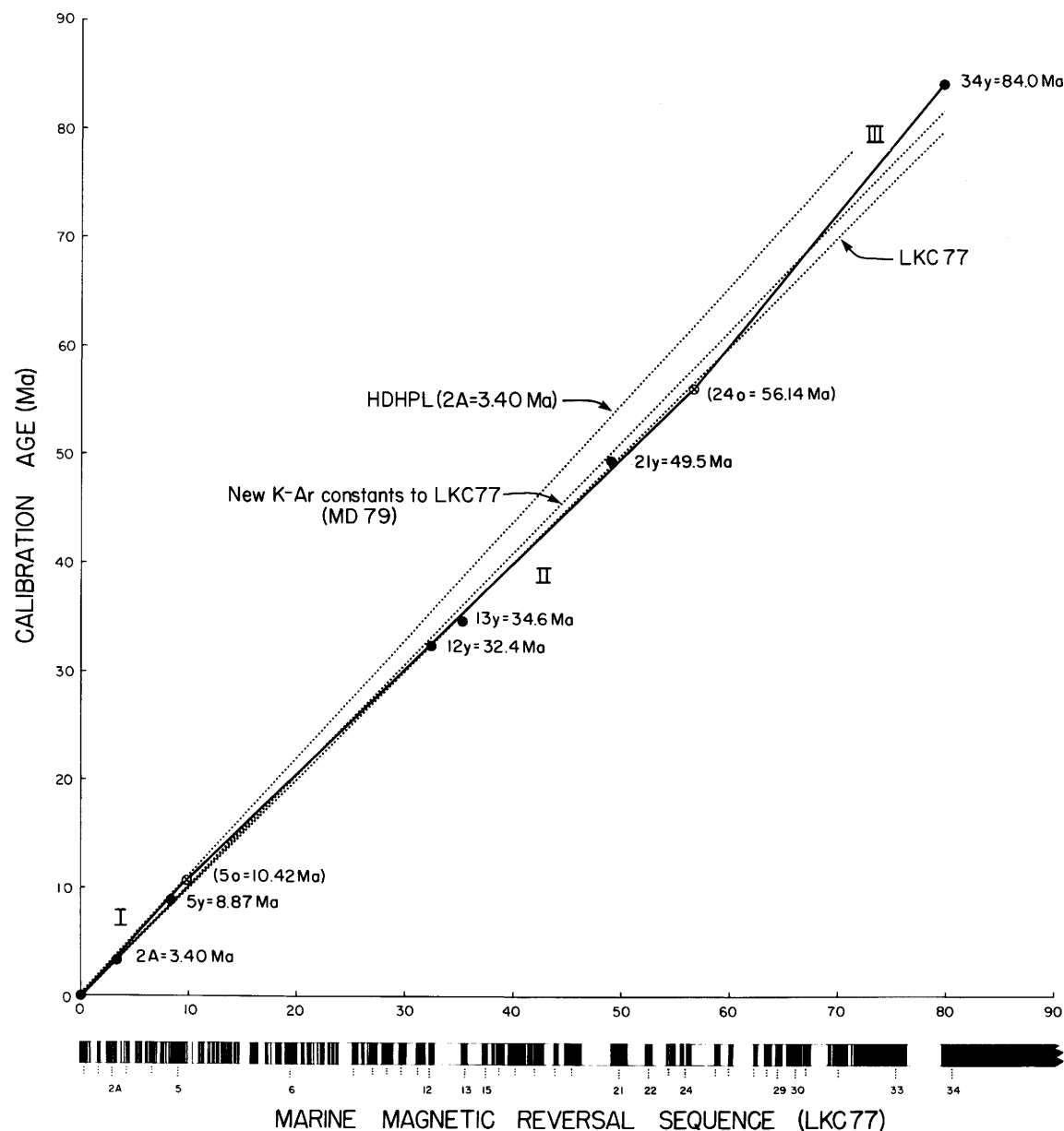


FIG. 1. Revised age calibration of marine magnetic reversal sequence from LaBrecque *et al.*, 1977 (LKC77). Solid lines are three linear apparent age-calibration age segments (I, II, and III) which satisfy calibration tie-points indicated by solid circles (Table 1). The two open circles with X's at anomalies 50 and 240 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 *et al.* (1968) (HDHPL68 with anomaly 2A set to 3.40 Ma to conform with current estimate) and LaBrecque *et al.*, 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).

C5 (8.87 Ma, item b, above) is very near to the age extrapolated for this anomaly in HDHPL68 (8.92 My, using the revised 3.40 Ma date instead of 3.35 Ma from Chron C2A). This is a strong indication that the original HDHPL68 time-scale provides a good chronologic framework for polarity reversals at least as far back as this time. Beyond Chron C5, calibration tie-points c, d, and e fall off from what would be the extension of the HDHPL68 trend (Fig. 1) and seem to define a different linear relationship between calibration age and apparent age; the change apparently occurs somewhere between the top of Chron C5 (item b) and the top of Chron C12 (item c). This new trend, however, cannot also accommodate the calibration tie-point for Chron C34 (item f) and a change to another relationship must therefore occur somewhere between Chron C21 (item e) and Chron C34 (item f).

A minimum of two changes in the relationship between

calibration age and apparent age in modified LKC77 appear to be required to satisfy this set of data. Consequently, we divide the geomagnetic reversal sequence into three linear calibration age-apparent age segments with the inflection points placed at anomaly 5 and at anomaly 24 for reasons discussed in Berggren *et al.* (this volume). Segment I extends from the origin to anomaly 5 and its slope in Fig. 1 is defined on the basis of items a and b plus the origin. This trend is extrapolated to derive an estimated age of 10.42 Ma for the older end of anomaly 5. Segment II is based on a linear best-fit through the data of items c, d, and e while constrained to join segment I at the derived age for the base of anomaly 5. Segment III is simply an interpolation between the estimated age of anomaly 24, derived by extrapolation of segment II, and the inferred age of anomaly 34 (item f).

Ages for magnetic polarity intervals or chrons are cal-

TABLE 1 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	5A	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

culated according to the linear equations of these three segments; a tabulation of these ages is presented in Table 1.

Direct bio-magnetostratigraphic correlations are the basis for comparison of the revised magnetochronology and biochronology. These correlations are discussed for the Paleogene in Berggren *et al.* (this volume) and for the Neogene below, and the resulting magnetobiochronology is shown in Fig. 3. In these correlations, the base of the Neogene is placed within Chron C6CN, at an estimated magnetochronological age of 23.7 Ma. This age estimate is not totally independent of biochronology because calibration data in c, d, and e, which define segment II, rely in part on biostratigraphic correlation. Calibration data (origin and items a and b) which define the initial segment (I), however, are totally independent of biostratigraphic control: the 3.40 Ma radiometric age for the base of the Gauss Chron and the 8.87 Ma radiometric age for the top of Chron C5 (Chron 11)

are based on lavas and are correlated to the marine magnetic polarity sequence primarily by the palaeomagnetic reversal signature. It is ironic that in the Paleogene and older periods, biochronological data tend to be used for age calibration of the magnetic reversal chronology (e.g., Lowrie & Alvarez 1981) whereas at least in the younger half of the Neogene, magnetochronology is often the basis for biochronological estimates. The potential for circular reasoning in the construction of an internally consistent geological time-scale should be kept in mind.

The Oligocene–Miocene boundary

'The Oligocene–Miocene boundary is one of the most difficult and controversial boundaries in the Tertiary' (Jenkins, 1966: 11). Seventeen years later little has changed if one considers the continuing polemics which take place at the quadrennial meetings of the Committee on Mediterranean Neogene Stratigraphy, those of the IGCP 114 (Pacific Neogene Datum Events), and those of the IUGS Working Group on the Paleogene–Neogene Boundary (Cati, (ed.) 1981) as well as in the biostratigraphic literature in general.

The problem lies, primarily, in the fact that no major, global regression event(s), such as those that occur at the Cretaceous–Tertiary, Eocene–Oligocene, or Miocene–Pliocene boundaries is recognized at the Oligocene–Miocene boundary, which coincides with a period of moderate to high sea-level stand. Thus, dramatic faunal, climatic and palaeo-oceanographic changes do not attend the base of the Miocene, and for this reason it has been difficult to determine definitive biostratigraphic criteria in recognizing and correlating the base of the Miocene and, by definition, the base of the Neogene, on a global scale.

Zonation by calcareous plankton of upper Oligocene to lower Miocene marine sedimentary sections has been the subject of considerable controversy since the basic zonations were developed by Bolli (1957) and Martini (1971) on planktonic foraminifera and calcareous plankton, respectively. We shall discuss the problems associated with recognizing this boundary in terms of both groups of microfossils.

The zonal scheme proposed by Blow (1969), not unlike that proposed earlier by Bolli (1957) and Bolli & Bermudez (1966), is based upon the following sequence of biostratigraphic events/ranges (in stratigraphic order):

4. FAD (first appearance datum) of *Globigerinoides primordius*.

3. FAD of *Globorotalia kugleri*.

2. continued (partial) range of *Globigerina ciperoensis* or *G. angulisuturalis*.

1. LAD (last appearance datum) of *Globorotalia opima opima*.

Our own observations at DSDP Site 516 (Rio Grande Rise, South Atlantic) indicate the following succession of events (in stratigraphic order):

4. FAD *Globorotalia kugleri*

3. continued (partial) range of *Globigerina angulisuturalis*

2. FAD *Globigerinoides primordius*

1. LAD *Globorotalia opima*

Note the inversion between the FAD's of *G. primordius* and *G. kugleri*. Similar observations have been made by others on the relationship of the FAD of *Globigerinoides primordius* relative to other taxa.

Biostratigraphic data gathered over the past decade,

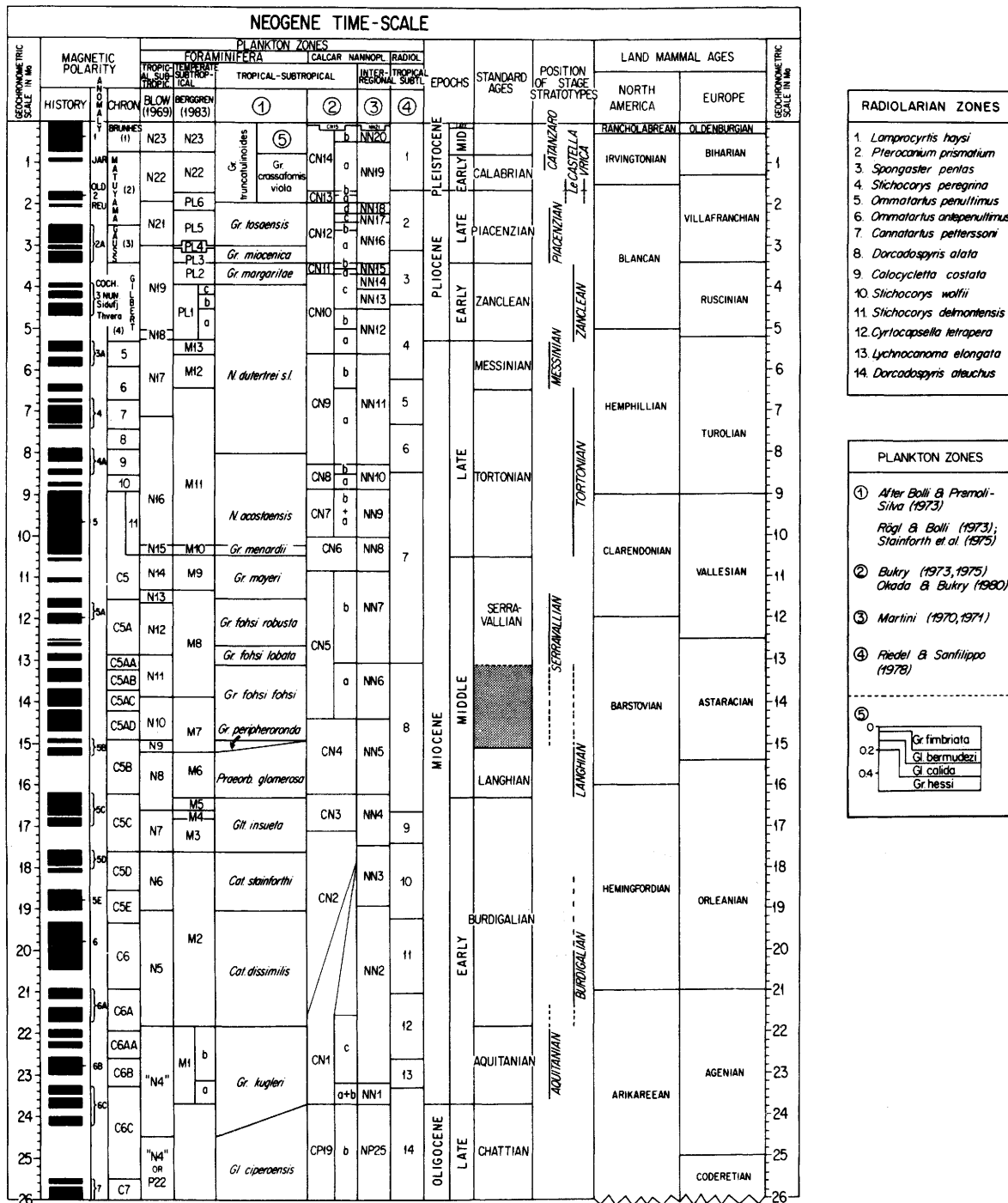


FIG. 2. Neogene geochronology. The geochronologic scale at the margins of the figure is derived from the magnetic polarity chronology which is in turn derived from palaeontologically and/or palaeomagnetically controlled radiometrically dated calibration points in the late Neogene, early Oligocene, middle Eocene and late Cretaceous (see text for further explanation). The position of the calcareous plankton zonal boundaries is based, for the most part, upon direct (first order) correlation between biostratigraphic datum levels and palaeomagnetic polarity stratigraphy as determined in deep sea cores or continental marine sediments (see compilation in Vincent, 1981a, b; Appendix II, this paper). In this way a true 'magnetobiochronology' is possible. 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.

primarily in connection with the Deep Sea Drilling Project, has provided additional information, but often it appears to be of a conflicting nature. Whereas the FAD of the genus *Globigerinoides* (as *G. primordius*) was thought to be a reliable marker for the Oligocene–Miocene boundary by many workers, the apparent time-transgression of its FAD relative to other biostratigraphic markers led Lamb &

Stainforth (1976) to suggest that it be abandoned as a precise index form for the Oligocene–Miocene boundary.

In his redefinition of Zone N4, Blow (1969: 222–225) replaced the concept of a *Globorotalia kugleri* Total-range Zone with a Concurrent-range Zone (with *Globigerinoides primordius*). He was of the opinion that the FAD of *G. kugleri* occurred within his Zone N3 (= P22), and his

(revised) Zone N4 was based on the extension of the range of *G. kugleri* into the time following the FAD of *G. primordius*.

The recognition of *Globigerinoides primordius* in pre-Aquitainian levels in the Aquitaine Basin of SW France (Scott 1972) and the Rhone Valley (Anglada 1971) as well as in the Codrington College section of Barbados (in calcareous nannoplankton Zone NP25 and above the LAD of *Globorotalia opima*; Van Couvering & Berggren 1977) had the effect of reducing the span of Zone NP22. The presumed overlap of *G. primordius* and *G. opima* in the Ashmore Reef No. 1 well, north-west Australia (Chapronière *in*: Shafik & Chapronière 1978; Chapronière 1981), if validated elsewhere, would effectively eliminate Zone P22 from the planktonic foraminiferal hagiography. However, we remain sceptical of the suggested overlap in these taxa (the specimens of *G. opima* are not unequivocal) and recent magnetobiostratigraphic studies in the South Atlantic have indicated a distinct separation between these two taxa (LAD *G. opima* associated with Chron C9N; FAD *Globigerinoides* associated with Chron C6CR. The FAD of *G. primordius* earlier than that of *G. kugleri* and, in fact, virtually coincident with the LAD of *G. opima opima* and within the later part of the ranges of the calcareous nannoplankton taxa *Reticulofenestra bisecta*, *Cyclicargolithus abisectus* and *Zygrhablithus bijugatus* has been recorded by Báldi-Beke *et al.* (1978) in the Piedmont Basin of NW Italy. Nevertheless, adequate documentation (in the form of unequivocal illustrations) is still lacking.

Thus the fact that the genus *Globigerinoides* (*G. primordius*) appears before the FAD of *Globorotalia kugleri* effectively eliminates the utility of Zone N4 (as emended by Blow 1969: 223, who had the order of appearance of the two nominate taxa reversed). For if the primary definition of Zone N4 is the FAD of *G. primordius* (Blow 1969), N4 is no longer a Concurrent-range Zone and there is a considerable gap between the sequential FADs of *G. primordius* (within either Zone P22 of Blow 1969 – and perhaps even earlier – and NP25; Martini 1971) and *G. kugleri* (base Zone N4, Blow, 1969, and NN1; Martini 1971).

The absence of a clearly defined boundary stratotype section for the base of the Aquitanian coupled with the lack of distinctive faunal and floral elements useful in regional correlation is responsible for the continued polemics surrounding the biostratigraphic correlation of the Oligocene–Miocene boundary.

In order to determine which of the biostratigraphic criteria among the calcareous plankton are most suitable for recognition and correlation of the Oligocene–Miocene boundary we must consider first the biostratigraphic relationships that exist in the stratotype section(s) and in the deep sea where richer faunas and floras occur.

Studies of the planktonic foraminiferal faunas of the stratotype (and nearby area) Aquitanian–Burdigalian sections have spanned the past quarter of a century. An analysis of the various papers that have appeared during this time suggests that the stratotype limits of the Aquitanian Stage lie within the concurrent ranges of *Globorotalia kugleri*, *Globigerinoides primordius*, *Globigerina woodi* and *Globoquadrina dehiscens* (Jenkins 1966; Pujol 1970; Poignant & Pujol 1976; Müller & Pujol 1979). The stratotype limits of the Burdigalian Stage lie within the concurrent range of *Globigerinoides altiapertura* and *Globoquadrina dehiscens* (Jenkins 1966; see also Anglada 1971; Poignant & Pujol 1976, 1979; Müller & Pujol 1979). *Globigerinoides altiapertura* first appears in the Burdigalian Stage (Jenkins 1966) and in Zone N5, above the LAD of

Globorotalia kugleri (Chapronière 1981).

A consideration of the above studies in the stratotype area suggests, then, that the Oligocene–Miocene boundary (base of the Aquitanian Stage) lies somewhere within the NP25–NN1 interval and within the range of *Globorotalia kugleri* (= N4 as a total range Zone).

Let us turn our attention now to a consideration of the way in which biostratigraphers have viewed the Oligocene–Miocene boundary particularly as a result of deep sea drilling. In the discussion ahead the reader is referred to Tables (4) and (5) (Appendix I) in which the relationships between various biostratigraphic datum events in the planktonic foraminifera and calcareous nannoplankton, respectively, are shown.

The many criteria used in deep-sea studies to delineate the Oligocene–Miocene boundary are expressed both in the calcareous nannoplankton and planktonic foraminifera.

1. *Calcareous nannoplankton*: the Oligocene–Miocene boundary has been placed according to each of the following criteria:

- I. NP25/NN1 boundary;
- II. A level within Zone NN1 (defined by the LAD of *Reticulofenestra (Dictyococcites) bisecta*); or
- III. The NN1/NN2 boundary (defined by the FAD of *Discoaster druggii*)

In the first case, that of (I.) the NP25/NN1 (or its equivalent) boundary, this level in itself is determined by various criteria, as follows:

	Remarks
(a) LAD <i>Reticulofenestra bisecta</i> (+ <i>R. scissura</i>)	Wide geographic distribution near shore and open ocean.
(b) LAD <i>Sphenolithus ciperoensis</i>	Tropical-subtropical species.
(c) LAD <i>Helicosphaera recta</i>	Predominantly hemipelagic; usually rare.
(d) LAD <i>Reticulofenestra scrippsae</i> (+ <i>R. hesslandi</i>)	Predominantly high latitude; near shore and open ocean.
(e) LAD <i>Zygrhablithus bijugatus</i>	Predominantly high latitude, epicontinental — near shore.

The LADs of *S. ciperoensis*, *R. bisecta* and/or *H. recta* are generally separated by a distinct stratigraphic interval (sites 149, 151, 167, 238, 289, 357, 363, 445, 516F, 522); less frequently they are found to occur (virtually) simultaneously (as at sites 74, 236, 296). The LADs of *S. ciperoensis* and *C. abisectus* have been recorded simultaneously (as in Site 171) as well as those of *R. bisecta* and *C. abisectus* (Site 234). In one instance (Site 386) the virtually simultaneous extinction (LAD) of three of the nominate taxa for the NP25/NN1 boundary (*S. ciperoensis*, *R. bisecta* and *H. recta*) is recorded with the FAD of *D. druggii* (nominate taxa of Zone NN2) and the LAD of *C. abisectus* (nominate taxa of the lower subzone of Zone NN1). In this instance one may ask where is Zone NN1 or better, *what is Zone NN1?*

2. *Planktonic foraminifera*: in deep-sea studies, each of the following criteria have been used to identify the Oligocene–Miocene boundary:

- (a) FAD *Globigerinoides primordius*
- (b) FAD *Globorotalia kugleri*

- (c) LAD *Globorotalia kugleri*
 (d) FAD *Globoquadrina dehiscens**

Comparing the zonal boundary definitions, those of the planktonic foraminifera appear to be more consistent than within the calcareous nannoplankton. However, as we have seen above, the temporal uncertainty due to the variations in relative position of the biostratigraphic datum events near the boundary is essentially comparable in the two groups of calcareous microfossils (c. 2–3 m.y.). The different evaluations permitted by this uncertainty are legion.

The NP25–NN1 boundary (based on LAD of *R. bisecta*) is found to lie close to that of the FAD of *G. kugleri* in some instances (sites 74, 296, 516F). The NP25–NN1 boundary (based on the LAD of *S. ciperoensis*) is close to that of the FAD of *G. kugleri* at Site 214.

An Oligocene–Miocene boundary based on the FAD of *Globigerinoides* (*G. primordius*) has been placed rather consistently in Zone NN1 (sites 149, 214, 238, 292, 296, 354, 357, 362, 363, 386), more rarely within Zone NN2 (Site 289). However, the FAD of *Globigerinoides primordius* is known to occur within Zone NP25 at some sites (e.g. 516) and has been documented to occur within this zone in various land sections and deep sea cores elsewhere.

The Oligocene–Miocene boundary based upon the FAD of *Globoquadrina dehiscens* has been observed either below the FAD of *D. druggii* (sites 296, 357, 522), above it (354, 356, 362, 363), or coincident with it (516F). The discrepancy here may well lie with the difficulty of determining in a consistent manner the FAD of *G. dehiscens*.

The relationship of the LAD of *C. abisectus* to the FAD of *D. druggii* is seen to be inconsistent also, occurring below in some instances (sites 296, 354, 357) as would be expected if *C. abisectus* is the nominate taxon of a lower subzone of Zone NN1, but above *D. druggii* in other instances (sites 356, 362, 363, 386, and 516F). Indeed, the taxon *C. abisectus* has been recorded up to the middle Miocene (Zone NN6).

It will be readily seen from the above that the inability to distinguish clearly between zones NP25 and NN1 may be responsible, in part, for the correlation of the FAD of *G. kugleri* to Zone NP25 in some, and to NN1 in other, deep sea drilling reports. Last occurrences (extinctions) are less than useful criteria in defining calcareous nannoplankton zones (unless done in a quantitative manner) owing to the problems of reworking. Alternatively the failure to distinguish between the components of the *Globorotalia kugleri* plexus (*G. kugleri*, *G. mendacis*, *G. pseudokugleri*) may also contribute to inconsistent biostratigraphic determinations of the 'FAD' of *G. kugleri* and the base of Zone N4.

Where then does the base of the Aquitanian (and, by extension, the Oligocene–Miocene boundary) lie with respect to the established calcareous plankton zones and/or datum levels discussed above? Inasmuch as we have shown that *Globigerinoides* appears at least as early as *Globorotalia kugleri* and that *Globoquadrina dehiscens* occurs within the range of *G. kugleri*, we would suggest that the base of the Aquitanian Stage should be relocated at a level immediately above the base of the present stratotype section (which is characterized at its base by an unconformity) and that it corresponds to the FAD of *Globorotalia kugleri* (= base N4

as a total range Zone) and to the NP25–NN1 Zone boundary (as defined by the LAD of *Reticulofenestra bisecta*). The FAD of *Globoquadrina dehiscens* appears to occur only slightly subsequent to that of *G. kugleri* and would serve as a secondary criterion in recognizing the approximate position of the Oligocene–Miocene boundary. Indeed Srinivasan & Kennett (1983) have chosen the FAD of *Globoquadrina dehiscens* as the definitive criterion in recognizing the Oligocene–Miocene. The boundary as recognized here corresponds to the lower part of Chron C6CN (c. 23.7 Ma); the boundary as recognized by Srinivasan & Kennett is approximately correlative with upper part of Chron C6CN, c. 23.2 Ma (see Table 6, Appendix II). The relationship is not unlike that which exists between *Globorotalia truncatulinoides*, *Globigerinoides obliquus extremus* and *Globigerinoides fistulosus* — taxa with sequential FAD's or LAD's that bracket the Pliocene–Pleistocene in different latitudes. The base of the Burdigalian Stage might then correspond closely to the N4/N5 boundary (Blow 1969) and the NN1/NN2 boundary (Martini 1971).

This conclusion appears to be consistent with those of some other authors. For instance, on the basis of a comparative study of the Soustons well (subsurface Aquitaine Basin) Vigneaux *et al.* (1970) suggested that the base of the Aquitanian coincides approximately with the appearance of *Globorotalia kugleri*. On the basis of a quantitative comparative study of the genus *Globigerinoides* Scott (1968, 1971) suggested that the stratotype Aquitanian straddled the *Globorotalia kugleri* and *Catapsydrax dissimilis* (= N4–N5) Zones.

Despite the cautionary note sounded by Blow (1969: 224) about the problem of confusion with *G. mendacis* and *G. pseudokugleri*, we believe that *G. kugleri* is basically a distinct taxon that is relatively easy to identify in a consistent manner (see in this context Chapronière 1981; p. 126, fig. 12).

We believe that part of the reason for the inconsistency in the data concerning the initial appearance of the genus *Globigerinoides* may be due to the effects of dissolution in deep sea cores and of geographic distribution in land sections. A further problem in the cross correlation of zones and datum levels based on calcareous plankton may lie in the difficulty in distinguishing consistently between calcareous nannoplankton Zones NP25 and NN1 as we have indicated above.

Magnetobiostratigraphic correlations (see above) suggest that the Oligocene–Miocene boundary (as limited by the FAD of *Globorotalia kugleri* and the LAD of *Reticulofenestra bisecta*) is associated with lower Chron C6CN and has an estimated magnetostratigraphic age of 23.7 Ma. This age estimate is seen to be remarkably consistent with published radiometric data, which suggests an age of 23 Ma (Kreuzer *et al.* 1980) to 24 Ma (Ritzkowski 1982) for the Oligocene–Miocene boundary (see additional discussion in Berggren *et al.*, this volume).

Corroborative evidence comes from California. Miller (1981), in study of the Zemorrian–Saucesian interval, recalculated the K–Ar dates reported by Turner (1970) using new decay and abundance constants (Steiger & Jäger, 1977). Accordingly, the Upper Zemorrian Iversen Basalt of Point Arena would now have an average age of 23.8 Ma; lower Saucesian volcanics from the San Emigdio Mountains, 22.5 Ma; and Upper Zemorrian or Lower Saucesian Santa Cruz Volcanics, 23.7 Ma. Taken together, these dates suggest that

* Widespread in the oceans; the other two are restricted to tropical-subtropical palaeoenvironments.

the Zemorrian–Saucesian boundary, correlated earlier to the N4–N5 boundary (Van Couvering & Berggren 1977), has an age of *c.* 23 Ma.

This date is too old for the N4–N5 boundary, at 21.8 Ma in our present time-scale (Fig. 2), and in addition it is even more inconsistent with offshore correlation of the Zemorrian and Saucesian to calcareous nanoplankton zones, as recently published by Crouch & Bukry (1979) and Arnal (1980). Despite their other differences, these authors agreed that in dart core samples from the California shelf, Zemorrian and Saucesian benthic foraminiferal assemblages overlap throughout the *Sphenolithus belemnus* (CN2) Zone of Bukry (1973, 1975). According to these observations, and the principle of exclusion that 'base defines boundary' in overlapping sequences, the offshore Zemorrian–Saucesian boundary corresponds to the base of the Saucesian faunas near the lower boundary of Zone CN2, where it would be calibrated at 18 Ma (Bukry 1975; see also Fig. 2).

Evidence from standard sections on shore, however, indicate that in fact the Saucesian benthic foraminiferal assemblages range down to well below the CN2 level, as the dating has suggested. In the type section at Los Sauces Creek, beds of the uppermost Zemorrian (by exclusion), lying just below and conformable with basal Saucesian, contain coccoliths that are referable to uppermost Oligocene *S. ciperensis* (CP19) Zone, and possibly the lowermost Miocene (*C. abisectus*, CN1a Zone) according to R. Z. Poore (written communication, 1981). In sediments associated with the 23.8-Ma Iversen Basalt of Point Arena, also of latest Zemorrian age, the base of the Miocene—as correlated by coccoliths (see above) — is identified by the LADs of *Reticulofenestra bisecta* and *R. scrippsae* (given as *Dictyococites bisectus* and *D. scrippsae*) in a low-diversity but diagnostic nanoflora collected by Miller (1981). Thus, in California, the 23 Ma Zemorrian–Saucesian boundary in standard sections can now be placed more accurately below the N4–N5 boundary and just above the Oligocene–Miocene boundary. In addition, the Oligocene–Miocene boundary is linked directly to Iversen Basalt, convincingly dated to 23.8 Ma, in remarkably close agreement with the 23.7 Ma date obtained by linking this boundary biostratigraphically to Chron C6CN.

The Miocene

A more or less standard threefold Miocene chronostratigraphic subdivision is followed here, in which the Aquitanian and Burdigalian ages represent the early Miocene, the Langhian and Serravallian ages represent the middle Miocene, and the Tortonian and Messinian ages represent the late Miocene.

The base of the Miocene (= Aquitanian) is understood to be limited by the FAD of *Globorotalia kugleri* and the LAD of *Reticulofenestra bisecta*; to be approximately coincident with the NP25–NN1 (CP19–CN1) boundary; to be associated with the early part of Chron C6CN; and to have an age estimated by magnetostratigraphy at 23.7 Ma (see above and Appendix II). The Burdigalian stratotype has a planktonic foraminiferal fauna indicative of Zone N5 (Anglada 1971) and NN2 (*druggi*, or CN1c; Müller *In*: Bizon & Müller 1979) or NN2–NN3 (*druggi-belemnus*; Schmidt *In*: Benda *et al.* 1977; see also Van Couvering & Berggren 1977). In California, stratigraphic levels referable to the Saucesian Stage belong mainly to the *Sphenolithus belemnus* (NN3 or CN2) Zone,

but according to Warren (1980) its lower part may include strata that can be assigned to the *druggi* (CN1c) Subzone and perhaps the *deflandrei* (CN1b) Subzone of the *Triquetrorhabdulus carinatus* (CN1) Zone of Bukry (1973). As we have noted above, R. Z. Poore (written communication, 1981) suggest that the youngest pre-Saucesian strata at Los Sauces Creek, California are of CP19 to CN1a age. Recalculation of radiometric dates (Turner 1970) from California suggests an age in this region of 23 Ma for the Saucesian–Zemorrian boundary and of 23.8 Ma for the CP19–CN1 boundary (Miller 1981).

In terms of magnetobiostratigraphy the following points are pertinent:

1. DSDP Site 15 was drilled on anomaly 6 in the South Atlantic and the oldest sediments above basement belong to Zone N5 (Blow 1970).
2. The FAD of *Calocyclus virginis* (radiolarian) occurs just below magnetic polarity Chron 20/21 (within C6A in terminology adopted in this paper) boundary and is closely correlative with the planktonic foraminiferal N4–N5 boundary (Theyer & Hammond 1974b).
3. The last appearance of *Globorotalia kugleri*, whose total range defines Zone N4, occurs in most cases between the base of Chron C6AN and the top of Chron C6AAN whereas the FAD of *Globigerinoides altiapertura* is associated with the top of Chron C6AN (*c.* 20.9 Ma), within Zone N5 (Appendix 1). The range of *G. kugleri* in the NW Pacific has been suggested to extend above the FAD of *G. altiapertura* (Keller 1981) and even above the FAD of *Globigerinoides trilobus*, in Zone N6.
4. In agreement with point (3), we note that in the Burdigalian sequence the FAD of *Globigerinoides altiapertura* also occurs in Zone N5 (Jenkins 1966), above the LAD of *Globorotalia kugleri* (Chapronière 1981), and also in Italian lower Miocene microfaunas (Borsetti *et al.* 1979).

Thus a comparison of calcareous plankton biostratigraphy in the stratotype Burdigalian with magnetobiostratigraphy of deep sea cores indicates that the Burdigalian is correlative with Chrons C6 and C6A at least.

Middle Miocene magnetobiostratigraphy has been a controversial topic during the past decade since the first attempt at integrating magnetic stratigraphy and biostratigraphy by Theyer & Hammond (1974a, b) and Ryan *et al.* (1974) and the (predominantly) biochronologic study by Berggren & Van Couvering (1974). Direct and indirect magnetobiostratigraphic correlations led Ryan *et al.* (1974) and Theyer & Hammond (1974a) to equate magnetic anomalies 5 and 5A with polarity Epochs (Chrons) 9 and 11, respectively rather than with Chrons 11 and 13, as implied earlier by Foster & Opdyke (1970). These correlations have essentially formed the basis for middle Miocene bio- and magnetobiostratigraphy during the past decade. New data from DSDP Sites 519 (Poore *et al.* 1983) and 558 and 563 (Miller *et al.* 1985) from the South and North Atlantic, respectively, have cast doubt upon these correlations and call into question the resulting magnetobiostratigraphy of the various biostratigraphic zones, datum events, and chronostratigraphic boundaries. In the discussion below we shall review the basic biostratigraphic framework of marine middle Miocene chronostratigraphy and present new data which requires a major revision to the magnetobiostratigraphy of this interval.

The middle Miocene (Langhian and Serravallian stage) is biostratigraphically bracketed by the FAD of *Praeorbulina glomerata curva*, nominate taxon of redefined Zone N8

(Jenkins *et al.*, 1981) which is associated with the younger part of Chron C5CN (16.5 Ma; see Appendix II) and the FAD of *Neogloboquadrina acostaensis*, one of the nominate taxa of Zone N16. This latter 'datum' was identified by Ryan *et al.* (1974) in the lower part of the stratotype Tortonian at Rio Mazzapiedi at a level said to be equivalent to a normal event assigned to magnetic polarity Epoch (Chron) 10. The base of the Tortonian was correlated with a slightly older level, correlated to Chron C5AN and Chron 11, whereas the remainder of the Tortonian was said to span the interval represented by Chrons 10 to 7. We shall show below that the base of the Tortonian probably corresponds to the base of Chron C5N, corresponding to Chron 11 in the original correlation of Foster & Opdyke (1970). We note in passing that the FAD of *Orbulina suturalis* is associated with the base of Chron C5BN (c.15.2 Ma; Appendix II). Our magnetobio-chronologic age estimate agrees precisely with the age assigned to this datum in Japan based on numerous radiometric age determinations bracketing this datum (Ikebe 1977) as well as with newly available dates on the Island of Martinique (Andreieff, pers. comm., February, 1984; see discussion below).

Calcareous nannoplankton studies suggest that the type Langhian belongs to Zones NN4, NN5 and NN6 (*partim*) (Martini 1968, 1971). The Cessole Formation, equivalent to a part of the Langhian, belongs to the *Sphenolithus heteromorphus* (NN5) Zone and the 'Transitional Unit' (between the Cessole Formation and the Serravalle Formation) in the Serravalle Scrivia section belongs to the *Discoaster exilis* (NN6) Zone (Müller 1975) and planktonic foraminiferal zones N9–N10 (Cita & Blow 1969) and the basal part of the overlying Serravalle Formation to the *Discoaster kugleri* (NN7) Zone (Müller 1975). The upper part of the Serravalle Formation at Serravalle Scrivia extends to the N13–N14 boundary (Ryan *et al.* 1974). In the Borbera section the 'Transitional Unit' belongs to Zone NN6 (Müller 1975) and corresponds to zones N11–N12? (Cita & Blow 1969).

Magnetostratigraphic studies, on the other hand, along the Bubbio-Casinasco Road have been subjected to alternative interpretations. Ryan *et al.* (1974: 647, 650) correlate the Langhian–Serravallian boundary with Chron C5BN at the base of Epoch (Chron) 15 on the basis of the occurrence of the '*Orbulina* Datum' just below the top of the Cessole Formation (which occurs within Chron 16). On the other hand, Nakagawa (1974) and Nakagawa *et al.* (1977) show the Langhian and Serravallian stages overlapping at the base of Chron 14 (which in the revised numeric system employed here would fall within the Chron C5AA–C5AB interval).

North Atlantic DSDP Site 396 was drilled on the eastern flank of the Mid-Atlantic Ridge and is situated between magnetic anomalies 5A and 5B (Schouten, pers. comm., January, 1984), *not* as originally reported, at anomaly 5 (Purdy *et al.* 1978: 119). The oldest sediments immediately above basement were placed in the *Globorotalia fohsi fohsi* Zone (Krasheninnikov 1978: 321) and the *Discoaster exilis* Zone (Bukry 1978: 309; note that Bukry, *loc. cit.*, states that Site 396 was drilled on the *western* flank of the Mid-Atlantic Ridge, on crust magnetized between magnetic anomalies 5A and 5B).

We have found (M-P. Aubry, pers. comm., January, 1984; Müller *et al.*, in press) that the NN5–NN6 (LAD *Sphenolithus heteromorphus*) and NN6–NN7 (FAD *Discoaster kugleri*) boundaries occur within Chron C5AD and within C5AA–C5AB interval, respectively, in DSDP Holes 558 and

563, i.e. between anomaly 5A and 5B correlatives. This latter correlation supports the studies on DSDP Site 396. We have, then, two options for drawing the Langhian–Serravallian boundary:

(a) base Chron C5BN which lies within Zone NN5 (Ryan *et al.* 1974: 665);

(b) at or near the NN6–NN7 boundary (Müller 1975) which lies within the Chrons C5AA–C5AB interval (Aubry *In: Miller et al.*, in press.)

There may be a stratigraphic hiatus between the Langhian and Serravallian stages but we see no evidence for this in the published literature dealing with the litho-, bio-, or magnetostratigraphy. Accordingly we show an interval of stratigraphic overlap between Chron C5BN and the Chron C5AA–C5AB interval corresponding to the uncertainty in placing this boundary based on the magnetobiostratigraphic interpretations of Ryan *et al.* (1974) or Nakagawa (1974), Nakagawa *et al.* (1977; see also Müller 1975). However, we favour the latter interpretation based on the evaluation of data presented here, i.e. in the Chron C5AA/C5AB interval.

In the Rio Mazzapiedi section the type Tortonian overlies the Serravallian but the youngest definitive age assignment within the Serravallian is Zone NN7 (Müller 1975). It is not possible to determine the biostratigraphic position of the upper part of the Serravallian and/or the Serravallian–Tortonian boundary based upon extant/published data.

In DSDP Hole 563 the *Sphenolithus heteromorphus* (NN5)/*Discoaster exilis* (NN6) boundary occurs in lower core 8 in the normal event (= Chron C5ADN) just above Chron C5BN (Müller *et al.*, in press) and within Zone N10. Zone NN7 spans the interval from the upper part of core 8 or lower part of core 7 to the lower part of core 4 (at least) (Chron C5AA/C5AB interval and the early part of C5). Zone NN7 brackets Chron C5AN and the FAD of *Globigerina nepenthes* occurs in core 5, just above Chron C5AN, i.e., within Zone NN7 (cf. discussion in Berggren & Van Couvering 1978: 43, 44). The upper limit of *Globorotalia fohsi robusta* (= N13) and the initial appearance of *G. nepenthes* (= N13–N14) are virtually coincident here, calling into question the validity of Zone N13 (cf. Blow 1969: 243–246; Berggren & Van Couvering, 1978: 46). At the same time the LAD of *Globorotalia siakensis* and the FAD of *N. acostaensis* are virtually coincident at the Chron C5N in Hole 563, calling into question the validity of Zone N15, as well.

The type Tortonian has been assigned to calcareous nannoplankton zones NN9–NN11 (*partim*) (Martini 1971, 1975) and to the *Globorotalia mayeri* — *G. linguaensis* through *G. menardii* — *Globigerina nepenthes* Zones (Cita *et al.* 1965) which correspond to Zones N15 through N17 (*partim*; Blow 1969; Cita & Blow 1969). The base of the stratotype Tortonian in the Rio Mazzapiedi section was assigned to the *Discoaster hamatus* (NN9) Zone based on the sole occurrence of the nominate taxon in sample 4 which was interpreted by Martini (1975) and accepted by Ryan *et al.* (1974) as the LAD of this taxon. This is the same level as the supposed FAD of *Neogloboquadrina acostaensis* in the Rio Mazzapiedi section (Cita *et al.* 1965). However, the lower 35–40 m of the Tortonian at Rio Mazzapiedi contain poor and undiagnostic microfossils and thus the occurrence of *N. acostaensis* and *D. hamatus* may, in fact, *not* be actual initial and terminal stratigraphic occurrences (see below). In fact, Ryan *et al.* (1974: 648, figure 4) indicate a stratigraphic range for *D. hamatus* extending over 100 m in the Rio Mazzapiedi section from

about 70 m below the base of the stratotype Tortonian and through the lower 35 m of the Tortonian, up to sample 4. This range, according to their interpretation, spans the interval between the normal event in Chron 12 to the normal event in Chron 10. However, there is no evidence for this range, (see Martini 1975 and remarks above). If this were true, however, it would place the *Discoaster coalitus* (NN8) Zone well down within the Serravallian, within Chron 12, and close to the base of Zone N14. Indeed, this is the interpretation made by Ryan *et al.* (1974: 655) and supported by independent arguments by Berggren & Van Couvering (1978: 44).

The presence of *D. hamatus* in the lower part, and the apparent FAD of *D. quinquerramus* in the upper part, of the type Tortonian, indicates that Zone NN10 is restricted to the Tortonian (Martini 1971, 1975; Ryan *et al.* 1974). Ryan *et al.* (1974: 649) indicate that the upper range of *hamatus* in piston core RC12-65 is limited to below magnetic Epoch (= Chron) 10/11 by dissolution, but that by cross correlation with piston core V19-99 it can be shown that the LAD of *hamatus* occurs within the brief stratigraphic range of the diatom *Coscinodiscus vetustissimus* var. *javanicus* which spans the normal polarity event of Chron 10, which in turn is correlated with the (supposed) LAD of *hamatus* in sample 4 of the stratotype Tortonian.

At DSDP Hole 519 *Catinaster coalitus* and *C. calyculus* occur sequentially in, and are restricted to, sediments of Chron C5N age (Poore *et al.* 1983: 131). Von Salis (1984: 425) has confirmed the association of these two taxa in Hole 521A with sediments interpreted as belonging to Chron C5 (Heller *et al.* 1984). These, and other related, data were subjected to two interpretations by members of the shipboard party of DSDP Leg 73:

1. The appearances of *C. coalitus* and *C. calyculus* were considered to have been delayed relative to their appearance in equatorial Pacific cores; thus the entire interval spanning Chron C5N and older sediments was correlated with Zone NN10 (Percival 1983).
2. The appearances of *C. coalitus* and *C. calyculus* were interpreted as being true FAD's, the bulk of Chron C5N sediments was correlated with Zones NN8 and NN9 and the basal 5 m above the sediment basement contact in Hole 519 Chron C5 was correlated with Zone NN7 (equivalent; Hsü *et al.* 1984: 628). An essentially identical interpretation was reached by Hsü *et al.* (1984) for Hole 521A based on the study of Von Salis (1984).

This latter interpretation conflicts with that proposed by Ryan *et al.* (1974) for this interval as observed by Hsü, La Brecque *et al.* (1984: 47) as well as with a K/Ar date of 11.4 ± 0.6 Ma (Dymond 1966) on an ash in the experimental Mohole Site of the east Pacific associated with the FAD of *Catinaster coalitus*. The supposed FAD of *C. coalitus* within Chron C5N yielded a magnetostratigraphic age estimate of 9.6 Ma in the chronology of Hsü, La Brecque *et al.* (1984).

Our own correlation over this interval is based upon studies in DSDP Holes 558 and 563. In DSDP Hole 563 the FAD of *C. coalitus* and *Discoaster hamatus* occurs in the reversed interval just below Chron C5N and within the lower part of Chron C5N, respectively (M-P. Aubry, pers. comm., January, 1984). Our magnetobiostratigraphic age estimate for the FAD of *C. coalitus* is 10.8 Ma which is significantly closer to the radiometric date of Dymond (1966) and helps, to some extent, resolve some of the discrepancy noted by Hsü, La Brecque *et al.* (1984: 47). Our results then, while generally

supporting the interpretation of Hsü *et al.* (1984) differ in a minor, yet significant way, with regard to their magnetostratigraphic correlation of the NN7-NN9 interval. In Hole 563 we have also found that the FAD of *Neogloboquadrina acostaensis* (Zone N16) occurs in core 4, at the base of Chron C5N, and with the range of *D. coalitus* (Zone NN8).

Our studies on the magnetobiostratigraphic correlations in DSDP Hole 563 (see Appendix II) have yielded additional data relevant to the late Miocene chronostratigraphy and magnetobiochronology (Miller *et al.*, in press). Thus the NN9-NN10 boundary (= LAD *D. hamatus*) is associated with the upper part of Chron C5N (8.85 Ma), the LAD of *D. bollii* (which occurs within Zone NN10) is associated with an interval of no palaeomagnetic data just below a normal event interpreted here as being the upper of the two normal events (8.3 Ma) associated with Chron C4AN. Forms transitional between *D. bellus* and *D. quinquerramus* (= NN10-NN11 boundary) occur in the normal event identified here as the upper normal event of Chron C4AN (8.2 Ma), consistent with the record of the FAD of *D. quinquerramus* of Haq *et al.* (1980: 430).

In summary our data indicate that:

- (a) Zone NN8 spans the base of Chron C5N.
- (b) Zone NN9 corresponds to the upper 3/4 of Chron C5N and extends into the reversed interval just above Chron C5N.
- (c) Zone NN10 extends from just above Chron C5N to C4AN.

From the data summarized above we can draw several conclusions and suggest some revisions to currently accepted magnetobiostratigraphic correlations.

1. The correlation of anomaly 5 with magnetic polarity Epoch (= Chron) 9 and anomaly 5A with Epoch (= Chron) 11 by Ryan *et al.* (1974) and Theyer & Hammond (1974a) is probably incorrect because Zones NN8 (*partim*), and NN9 can be shown to occur in sediments deposited during anomaly 5 time.
2. The Serravallian-Tortonian boundary probably lies at, or near, the base of Chron C5N, or at any rate is probably not older than the first normal event below Chron C5N. It probably lies within Zone NN8 and we place it here at the base of Chron C5N (= 10.4 Ma).
3. The realignment of calcareous plankton zones (and corresponding correlations with siliceous plankton zones) to magnetic anomaly correlates results in an approximately 1.5-2 my shift (toward younger age estimates) over part of the middle Miocene interval (see Appendix II for various datum levels recognized in this interval).

Late Miocene chronology of biostratigraphic and chronostratigraphic units remains essentially unchanged from earlier work. The Tortonian-Messinian boundary is correlated approximately with the FAD's of *Globorotalia conomiozea* and the *Amaurolithus delicatus-primus* group (see Appendix II) and antedates slightly the prominent carbon isotopic shift in the deep sea (Keigwin 1979; Haq *et al.* 1980; Vincent *et al.* 1980).

Integrated magnetobiostratigraphic studies on several upper Miocene sections on Crete have led to the correlation of several biostratigraphic events to a polarity sequence identified as Chrons 5 and 6 (Langereis *et al.* 1984). The initial appearance of *Globorotalia conomiozea* in a reversed interval between two normal events identified with Chron 5 (at 5.6 Ma) led to several conclusions:

- (a) The FAD of *G. conomiozea* in the Mediterranean (5.6 Ma) was interpreted as a delayed (migration) event, following

by approximately 0.5 my the initial evolutionary appearance of this taxon at *c.*6.1 Ma in the SW Pacific.

(b) Since the Tortonian–Messinian boundary is defined in the boundary stratotype section in Sicily at a level which coincides essentially with the initial occurrence of *G. conomiozea*, the authors suggest that the Tortonian–Messinian boundary has an age of about 5.6 Ma.

(c) Since the initial appearance of *G. conomiozea* on Crete (near the top of Chron 5) is below the level of the sinistral to dextral coiling change in *Neogloboquadrina acostaensis*, the latter event must be younger than the base of the Gilbert Chron (i.e. younger than 5.3 Ma).

(d) Since the coiling change in *N. acostaensis* occurred below the base of the Messinian evaporites, they in turn must lie wholly within the Gilbert Chron.

We have reservations about these conclusions. Briefly stated they are:

1. The sinistral to dextral coiling change in *N. acostaensis* has been previously shown to occur in the lower normal polarity event of Chron 5 in the Pacific (Saito *et al.* 1975) and eastern Atlantic, DSDP Site 397 off Cape Bojador (Mazzei *et al.* 1979) with a palaeomagnetic age estimate of 5.8 Ma.

2. The FAD of *Ceratolithus acutus* has been associated with a level approximately 6 m above the base of the Zanclean Stage (lower Pliocene; Cita & Gartner 1974) and shown to occur in the earliest Gilbert Chron (Mazzei *et al.* 1979; Berggren *et al.* 1983) with an estimated palaeomagnetic age of 5.0 Ma.

3. Keigwin & Shackleton (1980) identified a distinct carbon shift of about 0.5‰ in Chron 6 (*c.*6.3 Ma) in piston core RC12-66 just below a dextral to sinistral coiling change in *Neogloboquadrina acostaensis* in the younger part of Chron 6 (6.1 Ma) and the sinistral to dextral coiling change in *N. acostaensis* in mid Chron 5 (= Chron C3AN) (5.8 Ma) which is the same biostratigraphic event observed in the Mediterranean just below the evaporite series. This carbon shift has been subsequently observed in several DSDP sites from the Pacific and Indian oceans (Haq *et al.* 1980) and gives a slightly younger age (5.90–6.10 Ma based on a different magnetic polarity chronology). This carbon shift has also been observed in the Kapitean Stage of the Blind River section of New Zealand within Chron 6 with an estimated magnetochronologic age of 6.2–6.3 Ma and virtually coincident with the FAD of *Globorotalia conomiozea* in that section (Loutit & Kennett 1979). This same carbon shift has also been found in the Carmona-Dos Hermanos (stratotype Andalusian Stage) section in the Guadalquivir Basin of south-western Spain (Loutit & Keigwin 1982) over a stratigraphic interval which lies between the FAD of *Amaurolithus primus* (recorded as *Ceratolithus tricorniculatus* in Van Couvering *et al.* 1976) and calibrated to Chron 6 at *c.*6.5 Ma here (see Appendix II, Table 7) and the base of the Caliza Tosca (correlated biostratigraphically with the base of the Messinian evaporites). Inasmuch as it is almost certain that the carbon shift in the Carmona-Dos Hermanos section is identical to, and correlative with, the late Miocene carbon shift seen in the global ocean(s), we can correlate the carbon shift at approximately 6.1–6.2 Ma with a level at, or in close temporal proximity to, the base of the Messinian.

These data are consistent with the age estimate of about 5.3 Ma for the Miocene–Pliocene boundary and support our earlier estimates (Van Couvering *et al.* 1976) that the Messinian evaporites are approximately time correlative with the younger part of Chrons 5 and basal Gilbert. Burckle

(1978) has reached the same conclusion in correlating the Tripoli beds (unit 2) below the evaporites with the top of the reversed interval in Chron 5 in Capodarso, Sicily. Burckle & Opdyke (in press) have also correlated the base of the Caliza Tosca in the Andalusian Stage stratotype section with the same magnetostratigraphic interval. The age of the Tortonian–Messinian boundary remains somewhat controversial. It would appear to lie biostratigraphically close to the FAD's of *Globorotalia conomiozea* and *Amaurolithus tricorniculatus* over the range of 6.1–6.3 Ma. Magnetobiostratigraphic correlations by Ryan *et al.* (1974) suggested that the Tortonian–Messinian boundary was closely associated with the polarity Chron 6/7 boundary and the FAD of '*A. tricorniculatus*' (*c.*6.5 Ma). In this paper we retain this age estimate and place the boundary within the mid-part of Chron 6 coincident with the appearance of the earliest amaurolithids, *A. primus* (= including earlier references to *A. tricorniculatus*).

The regional magnetobiostratigraphic correlations discussed above suggest that the Cretan magnetic polarity sequence (Langereis *et al.* 1984) may have been misinterpreted. The Cretan correlations would be more consistent with published data if the normal polarity magnetozone above the FAD of *G. conomiozea* were identified with the lower normal of Chron 5. The remaining magnetic reversals below may then represent Chrons 6 and 7 (*partim*).

The revised middle and late Miocene magnetobiochronologic age estimates derived here are seen to be in remarkably close agreement with high temperature radiometric dates in Japan of 11.6 ± 0.4 Ma on the *Globigerina nepenthes* FAD (= N13–N14 boundary), 14.5 ± 0.4 Ma on the *Globorotalia peripheroacuta* FAD (= N9–N10 boundary), and interpolated biochronologic age estimates of *c.*11 Ma on the *Globorotalia siakensis* LAD (= N14–N15 boundary) and 10.0–10.5 Ma on the FAD of *Neogloboquadrina acostaensis* (= N15–N16 boundary) (Ikebe *et al.* 1981; cf. Tsuchi, (ed.) 1981).

Additional data comes from the Island of Martinique (Andreieff *et al.* 1976; P. Andreieff, pers. comm., February, 1984) where a series of intercalated sediments and basalt flows dated by the potassium argon method have yielded the following results (from older to younger):

(a) The *calcaires de Sainte-Anne* (*Globigerinatella insueta* Zone = Zones N7–N8) are bracketed by two basalt flows dated $17.8 \text{ Ma} \pm 1.8$ (at the base) and 15.9 ± 0.5 Ma (at the top).

(b) Les *calcaires du Francois* and the '*tufs*' de Bassignac (*G. peripheroronda* Zone = Zone N9) are separated from the *Tuffites du Marin* s.s. (*G. fohsi* — *G. fohsi lobata robusta* Zones = Zone N10–N12) by volcanic deposits dated at 15.0 ± 0.3 Ma.

(c) The top of the *Tuffites du Marin* s.s. (= lower part of *G. fohsi robusta* Zone = Zone N12) are overlain by a lava flow dated at 12.8 ± 0.6 Ma.

(d) The *Tuffites de Fort de France* (upper part of *Neogloboquadrina humerosa* Zone = top Zone N17, = Zone M12 and Zone M13 with *Globorotalia cibaoensis* — *G. margaritae* of Berggren *et al.* 1983) lie above an andesite dated at 6.4 ± 0.6 Ma.

These dates are seen to be in remarkably close agreement with the derived magnetobiochronology in this paper.

The Miocene–Pliocene boundary

The Miocene–Pliocene boundary was discussed in detail by

Cita (1975), who proposed a boundary stratotype section coincident with the base of the stratotype Zanclean stage at Capo Rosello, Realmonte, Province of Agrigento, Sicily. Cross-correlation between the biostratigraphically dated section at Capo Rosello and biostratigraphically and palaeomagnetically dated DSDP sites (125 and 132) in the Mediterranean led Cita (1975, 1976) to suggest that the Miocene–Pliocene boundary was biostratigraphically linked via the base of the *Sphaeroidinellopsis* Acme-Zone, with the upper part of palaeomagnetic polarity Chron 5 (= youngest part of Chron C3A) estimated to have an age of 5.3–5.4 Ma. However, the palaeomagnetic studies conducted on these cores are inadequate for a definitive identification of a polarity reversal history (Kennett & Watkins 1974) and studies by Berggren (1973) and Saito *et al.* (1975), among others, have suggested that the Miocene–Pliocene boundary is biostratigraphically linked via the LAD of *Globoquadrina dehiscens* and the FAD of *Globorotalia tumida* with the base of the Gilbert Chron, estimated to have an age of 5.3 Ma (Appendix I). Essentially similar conclusions have been drawn by Thunell (1981) and Van Gorsel & Troelstra (1981) who have made studies of low latitude planktonic foraminiferal successions in equatorial cores from the Atlantic, Pacific, Indian Ocean, and Indonesia, respectively.

The Pliocene

We follow previous usage (Berggren 1973; Berggren & Van Couvering 1974) in retaining a bipartite subdivision for the Pliocene of the Zanclean (lower) and Piacenzian (upper) stages. The relationship of these units to standard calcareous plankton biostratigraphy has been shown by Cita & Gartner (1974) and calcareous plankton biochronology of the Pliocene has been summarized by Berggren (1973). Over 30 planktonic foraminiferal and nearly 25 calcareous nannoplankton datum events have been palaeomagnetically correlated resulting in a high degree of biostratigraphic and biochronologic resolution within this geologically short (approximately 3.7 m.y.) epoch (Appendix II).

A recent study on the Lower Pliocene Suva Marl of Fiji (Rodda *et al.*, in press) is of particular interest to the Pliocene magnetobiochronologic framework presented here. By combining data on nearly 40 K/Ar (biotite) dates on volcaniclastic tuffs (ranging sequentially in age from c.4.8 Ma–3.8 Ma) in an approximately 180 m thick sequence of predominantly reversed polarity (but with three normal magnetozones identified as the Thvera, Sidufjall and Nunivak events of the Gilbert Chron) and calcareous plankton biostratigraphy, it has been possible to estimate ages for the normal polarity subchron boundaries as well as several biostratigraphic zonal boundaries and events. An age-stratigraphic height (relative to O-level marker bed) regression was used to estimate ages of the polarity boundaries which are seen to be in close agreement with the polarity scale of McDougall (1979) based predominantly on age and polarity data on subaerial volcanic rocks. Age estimates (in Ma) for the lower three normal events of the Gilbert Chron are compared below with those derived in this paper presented in parenthesis:

- Nunivak: 4.09–4.22 (4.10–4.24);
- Sidufjall: 4.52–4.67 (4.40–4.47);
- Thvera: 4.87–4.93 (4.57–4.77).

The differences in chronology of the lower two polarity subchrons is puzzling both in regards to age (the estimate of Rodda *et al.*, in press, are approximately 0.15 to 0.3 m.y.

older than ours) and duration. In the Suva Marl of Fiji the Sidufjall and Thvera Subchrons are shown to have durations of 150 000 years and 60 000 years, respectively, which is in inverse proportion to their respective durations as measured in sea floor anomaly profiles (Sidufjall: 70 000 years; Thvera: 200 000 years; Klitgord *et al.* 1975) and deep sea sediments (Sidufjall: 70 000 years; Thvera: 170 000 years; Opdyke 1972).

We note further that there are no constraints (by way of K/Ar dates) on the age of the lower normal magnetozones (= Thvera) in the Suva Marl inasmuch as the oldest K/Ar date of 4.8 Ma is from a stratigraphic level *above* the Thvera Subchron so that direct extrapolation from stratigraphically higher levels may not be yielding a reliable numerical value for this subchron.

Finally we note the close correspondence between the radiochronologic framework provided for early Pliocene calcareous plankton biostratigraphy on Fiji (Rodda *et al.*, in press) and the magnetobiochronology derived here (see Fig. 2 and Appendix II):

1. 33 K/Ar dates over the stratigraphic interval representing the combined Zones NN13 and NN14 range from 4.9 to 4.0 Ma with estimated boundary ages of 4.82 Ma (NN12/NN13) and 3.86 Ma (NN14/NN15) based on a best fit regression through the dated values. By comparison our magnetobiochronologic estimates for the NN12–NN13 and NN14–NN15 boundaries are 4.6 and 3.7 Ma, respectively.
2. 6 K/Ar dates from the same stratigraphic level within Zone NN15 yield average dates (on replicate samples) of 3.78 Ma, 3.74 Ma, and 3.65 Ma with an estimated age for the NN15–NN16 boundary of 3.52 Ma based on best fit regression through the dated values. By comparison our magnetobiochronologic estimate for the NN15–NN16 boundary is 3.5 Ma.

The Pliocene–Pleistocene boundary

The Pleistocene, and particularly its lower boundary, remains as controversial as ever. Recent summaries (Haq *et al.* 1977; Pelosio *et al.* 1980; Colalongo *et al.* 1981; Pasini & Colalongo 1982) have clarified the problems associated with an adequate definition in the Mediterranean of a Pliocene–Pleistocene boundary stratotype and its recognition elsewhere. It is now apparent that the over 300 m thick, mid- to upper bathyal, Vrica section, south of Crotona (Calabria) is more suitable as a boundary stratotype section (Selli *et al.* 1977) than the earlier nominees at Santa Maria di Catanzaro and Le Castella.

Integrated bio- and magnetostratigraphic studies suggested that the 'marker bed' at Le Castella is closely associated with a level coincident with, or slightly younger than, the top of the Olduvai Event, c.1.6 Ma (Haq *et al.* 1977). Investigations at the Vrica section are essentially complete. Biostratigraphic studies (Colalongo *et al.* 1981) indicate that the Pliocene–Pleistocene boundary, on palaeontological grounds, should be located within an approximately 36 m thick interval (the *e–m* interval) which extends from a distinct sapropel layer (*e*) to the level of occurrence of a distinct volcanic ash bed (*m*). This latter bed has been the subject of some considerable attention lately (Boelstorff 1977; Savelli & Mezzetti 1977; Selli *et al.* 1977). Obradovich *et al.* (1982) have recently shown that the previous age determinations attributed to this poorly-preserved ash, indicating an age over 2.5 Ma, have been mistaken. Samples from a second and much thicker ash, tens of metres downsection in Pliocene strata, were

apparently the source of the published ages. The 'Pleistocene ash' (level *m*) can only be said to be less than 1.9 Ma.

The (*m*) ash lies approximately 9 m above the FAD of *Cytheropteron testudo* and is essentially coterminous with the FAD of *Gephyrocapsa oceanica* (Colalongo *et al.* 1981). These authors have recommended that the Pliocene–Pleistocene boundary be placed at a level immediately preceding the FAD of *C. testudo*, the first of the so-called 'cold guests', or 'northern guests' (Suess 1983), whose appearance in the Mediterranean has been considered to denote the beginning of the Pleistocene Epoch.

Several planktonic foraminiferal events have been shown to span the *e–m* interval which may aid in recognition of the boundary (as formally proposed) in extra-Mediterranean regions. Calcareous nannoplankton (Backman *et al.* 1983) and palaeomagnetic stratigraphy (Tauxe *et al.* 1983) have recently been re-investigated in this section in an attempt to resolve previous discrepancies in interpretation. Two intervals of normal polarity separated by a short interval of reversed polarity have been identified as N1 and N2, respectively, in the lower part of the Vrica Section (Tauxe *et al.* 1983). A third normal polarity interval (N3) has been identified in the upper 40 m of the exposed section. The LAD's of *Discoaster brouweri* at the base of the lower (N1) normal interval and of *Cyclocolithus mcintyreii* about 56 m above the top of the second (N2) of the lower two normal events supports the identification of these two normal polarity intervals as the Olduvai Subchron. The physical horizon immediately below the initial appearance of *Cytheropteron testudo* is located about 9 and 10 m, respectively, above sapropel bed *e* and the top of N1 + N2 (= Olduvai Subchron) at about 1.6 Ma.

As this paper goes to press, members of the INQUA Subcommittee on the Pliocene–Pleistocene Boundary and of International Geological Correlation Project 41 (Pliocene–Pleistocene Boundary) are formulating a resolution regarding the (revised) definition of the Pliocene–Pleistocene boundary in the Vrica Section of Calabria, Southern Italy, to be submitted to the IUGS International Committee on Stratigraphy. This resolution will suggest locating the Pliocene–Pleistocene boundary stratotype at the top of marker bed *e* about 3–6 m above the top of the Olduvai normal polarity event. It will be seen that this recommendation results in continuity with some previous studies which placed the boundary at the top of the Olduvai Event, at *c.* 1.6 Ma (Haq *et al.* 1977; Berggren *et al.* 1980).

The Pleistocene

Attempts at formulating a unified Pleistocene chronostratigraphy have suffered from the climatic overprint which characterizes the late Neogene part of geologic time. The classic units have been recognized in northern Europe and have been correlated with the continuous oxygen isotope records from the oceans (Shackleton & Opdyke 1973, 1976) by means of the intermediate link of loess and terrace stratigraphy (Kukla 1970, 1975, 1977). Problems in classic stratigraphic subdivision of the Pleistocene have been compounded by the fact that it is now apparent that while the terraces representing the four classic Alpine 'glacial' ages cover the last 0.8 m.y., they correspond to both glacial and interglacial climatic intervals. Furthermore at least 17 glacials and interglacials have been recognized over the past 1.7 Ma in Europe, eight of which belong to the Brunhes Chron (last 0.73 m.y.). Some 23 oxygen isotope stages representing glacial-

interglacial cycles have been recognized in the deep sea since the late Jaramillo Subchron with nine of these cycles being confined to the Brunhes Chron (and corresponding to the eight glacial-interglacial cycles represented in the loess sequence of Europe). Thus the stratigraphic record upon which the classic North European Pleistocene chronostratigraphy is based represents but fragmentary portions of the total Pleistocene Series. This has led to both misunderstanding of the nature of the stratigraphic record and miscorrelation between the marine and continental record, and we would agree with Kukla (1977) in his call for elimination of classic climatostratigraphic units from the Pleistocene chronostratigraphic hagiography and substitution of the $\delta^{18}\text{O}$ record in deep sea sediments in their place.

It will suffice to point out here that the degree of chronologic resolution increases considerably as we approach the present time. In particular the oxygen isotope scale (stages 1–23), extending from the present day to the Jaramillo Subchron (*t* = *c.* 0.9 Ma), can discriminate essentially isochronous climatic cycles with a cyclicity of approximately 0.09 m.y. The use of Pleistocene biostratigraphic datum levels within a framework of oxygen isotope and magnetic-reversal scales leads to a further chronologic resolution on the order of 3000–5000 years (Berggren *et al.* 1980) in some instances. The relationship of Pleistocene calcareous plankton datum events to palaeomagnetic stratigraphy is shown in Table 7 (Appendix II). Spectral analysis of the $\delta^{18}\text{O}$ records in five deep sea cores by members of the SPECMAP project (Imbrie *et al.*, in press) has provided the basis for a revised chronology of the marine $\delta^{18}\text{O}$ record for the past 0.78 m.y. and provided strong evidence that orbital variations are the main external cause of the succession of middle and late Pleistocene ice ages.

At the same time, larger-scale perturbations of the climatic base-line are recorded in less sensitive marine systems, which show four principal climatic 'lows' (periods of maximum winter cold and maximum seasonality) at roughly 0.5 m.y. intervals during the Pleistocene, centred at 1.6, 1.0, 0.4, and 0.1 Ma (Briskin & Berggren 1975). These are, despite the imperfections of the continental record, clearly equivalent to distinct cold-climate intervals evident in mammalian biochronology (summarized by Berggren & Van Couvering 1974, 1979) and deserve to be recognized, at least in geohistorical scenarios, as the traditional 'Ice Ages' of Donau/Nebraskan, Günz/Kansan, Mindel/Illinoian, and Riss-Würm/Wisconsin.

The Marine Neogene time-scale: summary

Our assessment of palaeontologically correlated magneto-chronologic age estimates for the various Neogene boundaries, based on the revised magnetochronology presented here, are: Pliocene–Pleistocene (just above top Olduvai): 1.6 Ma; Miocene–Pliocene (basal Gilbert): 5.3 Ma; Oligocene–Miocene (mid Chron C6N): 23.7 Ma (see Fig. 2).

Features of interest in this revised Neogene time-scale include the following:

1. The genus *Globigerinoides* appears sporadically as early as Chron C7N (*c.* 26 Ma) but attains numerical prominence in deep sea faunas only in the latest Oligocene (in the reversed interval just below Chron C6CN). It thus retains its usefulness as a guide to the approximate position of the Oligocene–Miocene boundary.

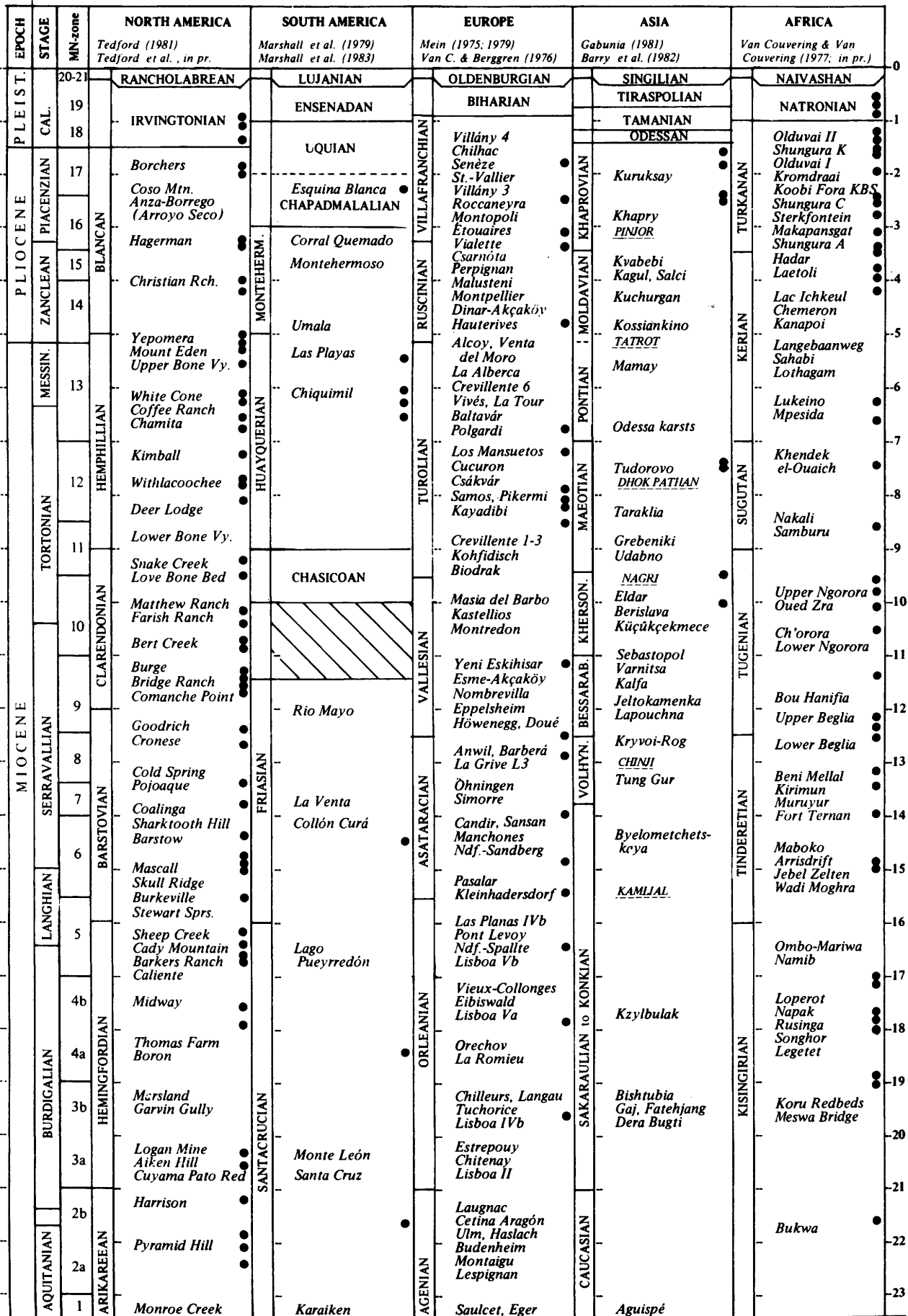


Fig. 3. Neogene continental time-scale. Principal mammal faunas from the Neogene of the indicated regions are shown in relative biochronological order, and are positioned, within the limits imposed by the medium, according to best estimates of absolute age. The biochron boundaries are dated to the nearest 0.5 Ma, except where better control is available, according to the estimated ages of the included faunas. 'MN-zone' (column 3) gives the suggested calibration for the divisions of European 'Mammal Neogene' biochronology defined by Mein (1975, 1979). Note that many major collections are from composite sections with a number of stratigraphically superposed faunal levels (e.g. Barstow; Santa Cruz; Samos; Maragheh; Lothagam). In these cases it is the 'main level,' or conceptual middle of the collection, the position of which is indicated. The Siwaliks 'mammal stages' (e.g. Nagri, Dhok Pathan), however, are shown according to the probable position of their respective bases. Black dots at the right side of each column denote radiometric age determinations in the regional mammal records, but not (necessarily) for any mammal fauna whose name is listed nearby. The dates are indicated mainly to give an idea of the level of radiometric control in our calibration.

2. Numerous biostratigraphic criteria have been suggested to correlate the position of the Oligocene–Miocene boundary from the Aquitanian stratotype. We have chosen the FAD of *Globorotalia kugleri* and the LAD of *Reticulofenestra bisecta*, both of which are associated with mid Chron 6CN, as the 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 (see item 14 in the Palaeogene chapter, and the discussion of California Zemorrian-Saucesian geochronology above).
3. The Aquitanian–Burdigalian boundary is correlated with the regional LAD of *Globorotalia kugleri* in Chron C6A time with an estimated magnetochronologic age of 21.8 Ma.
4. The lower Miocene stratigraphic interval encompassed by magnetic polarity Chrons C5D–C6AA contains few calcareous plankton datum events. However, at least 15 planktonic foraminiferal and five calcareous nannoplankton datum events occur in Chron C5B–C5C. The LAD of *Catapsydrax dissimilis* (= N6/N7 boundary) and the rapid sequential appearance of *Globorotalia praescitula* and *G. zealandica* occur near the Chron C5C–C5D boundary (c.17.5 Ma).
5. The lower–middle Miocene boundary (= base of the Langhian Stage) is biostratigraphically correlated with the FAD of *Praeorbulina glomerosa curva* which is associated with Chron C5CNI (the younger part of anomaly, correlative 5C) and which has an estimated age of 16.5 Ma.
6. The FAD of *Orbulina* (*O. suturalis*) occurs at the base of Chron C5BN with an estimated magnetochronologic age of 15.0 Ma, in precise agreement with recent assessment of radiometric dates that place the same numerical value on this datum level.
7. The middle–upper Miocene (= Serravallian–Tortonian) boundary is linked biostratigraphically with a level only slightly older than the FAD of *Neogloboquadrina acostaensis* near the base of anomaly 5 correlative (mid Chron C5 time) and has an estimated age of 10.4 Ma.
8. The base of the Messinian Stage is linked biostratigraphically with the FAD of *Amaurolithus primus* in mid-Chron 6 and has an estimated age of 6.5 Ma.
9. The Miocene–Pliocene (Messinian–Zanclean) boundary is linked biostratigraphically with the LAD of *Globoquadrina dehiscens* and the FAD of *Globorotalia tumida*, only slightly above the Gilbert/Chron 5 (Chron C3A) boundary at c.5.3 Ma.
10. Boundary age estimates and duration of informal divisions (in parenthesis) of the Neogene are as follows: early Miocene: 23.7 Ma–16.5 Ma (7.2 m.y.); middle Miocene: 16.5 Ma–10.4 Ma (6.1 m.y.); late Miocene: 10.4 Ma–5.3 Ma (5.1 m.y.); early Pliocene: 5.3 Ma–3.4 Ma (1.9 m.y.); late Pliocene: 3.4 Ma–1.6 Ma (1.8 m.y.); early Pleistocene: 1.6 Ma–0.73 Ma (0.87 m.y.); middle Pleistocene: 0.730 Ma–0.128 Ma (0.602 m.y.); late Pleistocene: 0.128 Ma–present (0.128 m.y.)

Continental biochronology and the palaeomagnetic time-scale

In the following section, the continental time-scale of the pre-Pleistocene Neogene, summarized in five regional syntheses of mammalian biochronology (see Fig. 3) is compared to the revised geomagnetic polarity time-scale, in order to test (as far as possible) our present assumptions about the internal accuracy of the GPTS. We note that the continental time-scale is primarily a framework of ‘hard’ K–Ar and zircon age determinations, which are much more available in mammal-

bearing deposits than in the deep-sea sequences.

The continental (mammalian) and marine (planktonic microfossil) biochronologies, each with their own time-scale, can be compared in two ways. The classical approach is by direct stratigraphic correlation of marine and nonmarine biostratigraphy in sequences where the fossils are, or can be made to be, relevant to regional calibrated biochronologies. The second, recently-developed approach, is to find (and accurately identify) geomagnetic polarity reversals in mammal-bearing strata. Although these are still as rare as good radiometric dates in marine pelagic sections, palaeomagnetic tie points provide more precise correlations than any other in common use. (In future, stable-isotope curves may be introduced into continental correlations, if the cyclic variations can be successfully indexed.)

All comparison points, or ‘tie points’ that we have selected are annotated below, together with brief discussions of regional stratigraphic syntheses from which the ‘tie points’ obtain their control. We have also included separate discussions of two of the most significant datum events in Neogene mammalian biochronology, the immigration of two horse genera into Eurasia, respectively the ‘*Hipparion* Datum’ and the ‘*Equus* Datum’, both of which have been related to the GPTS and numerous radiometric dates.

With some exceptions the marine and continental calibrations brought together at the ‘tie points’ agree to within 0.5 m.y. Most events in mammalian history, at least before the Pleistocene, cannot be correlated to marine history from biostratigraphic-radiometric information closer than this limit, while systematic deviations in comparing some of the superpositional sequences indicate the possibility of fundamental miscorrelations in these regions (e.g. central California and Vienna Basin mid-Miocene).

Regional mammal biochronology.

Current subdivisions of the mammalian history of North America, South America, Europe, non-oriental Asia, and Africa are presented in Figure 3. The radiometric calibration of these regional biochronologies are taken in large part from published reviews but we have also relied on original interpretations of the dating literature, especially with regard to western Europe and Africa. Faunal characterizations of the biochronological units are beyond the scope of this paper, and the reader should consult the indicated references. The North American land-mammal ages are the traditional ‘Wood Committee’ units, currently under review by Tedford *et al.* (in press). South American land-mammal ages were first outlined by Patterson & Pascual (1972). European mammalian biochrons were characterized in the so-called MN-zones by Mein (1975; see also Mein 1979), and incorporated into regional land-mammal ‘stages’ subsequently (see Fahlbusch 1976). The Asian biochrons are discussed by Gabunya (1981), with reference to central Asia and the Ukraine, and by Barry *et al.* (1982) with reference to the Indo-Pakistani sequence. The African biochrons given here are from a work in progress by J. A. Van Couvering & J. A. Harris (Van Couvering).

Hipparion datum.

The immigration of hipparionine equids into the Mediterranean and central European areas is the defining event for MN-9, the base of the Vallesian biochron (Mein 1979). Although the totally mistaken Pliocene correlation of

the 'Hipparion Datum' is no longer debated, the geochronometric age of this event continues to be argued between advocates of 10 Ma and 12.5 Ma. This debate has not been greatly advanced by a concurrent upheaval in the systematics of hipparions, which has cast into doubt the identity of 'the first hipparion' in many sequences. Resolution of the systematics, however, now suggests that the age debate concerns two different datum events: first arrivals of two different hipparions, in two different areas.

Forstén (1982) and MacFadden & Skinner (1982) recapitulated the rapidly-growing literature on the systematics controversy. The conservative position, upheld by Forstén, is that most, if not all, of Eurasian hipparions (including the type species, *H. prostylum* Gervais) evolved from *Hipparion primigenium* (von Meyer), a single and locally variable species found throughout Eurasia and North Africa at the beginning (by definition) of the Vallesian. The argument focuses on statistics of tooth and limb bone morphology. MacFadden & Skinner, who recognize 4 North American hipparion genera according to cladistic analysis based mainly on facial morphology (mainly the pre-orbital fossa shape and location), hold that hipparion dental and limb bone morphology is too conservative and repetitive for generic-level phylogenetic decisions (see also Woodburne & Bernor 1980; MacFadden & Woodburne 1982). In this view, a hipparion close to *Cormohipparion sphenodus* (Barstovian-Clarendonian, 13–11 Ma) reached the Old World and there gave rise to various hipparions with the 'Type 1' facial morphology (Woodburne & Bernor 1980), that characterizes all Vallesian hipparions. This was closely followed by the immigration, in early Turolian, of a species of true *Hipparion* closely similar to *H. tehonense* (early Clarendonian, 10–11 Ma). Many additional Old World species and genera evolved from these pioneers by later Miocene time (see MacFadden & Woodburne 1982). More to the point of the *Hipparion* – or hipparion – datum, however, is the fact that both parties agree that the Vallesian hipparions are monophyletic, whether belonging to the 'primigenium' morphogroup or to the 'Type 1' facial fossa group.

Berggren & Van Couvering (1978) cited a number of marine-nonmarine correlations and radiometric dates in the Middle Miocene of the Mediterranean-central European area, to narrow down the hipparion datum to a level equivalent to late Serravallian and to calibrate it to 12.5 Ma. Some of these limiting cases have been reinvestigated and their evidence confirmed, for instance Bou Hanifia and Kastellios (see below), which document medial Vallesian hipparion faunas in direct association with earliest Tortonian microfaunas. Further corroboration of this calibration comes from the Eastern Paratethys, where the Vallesian assemblages are equated with the Bessarabian Stage, the base of which is correlated to upper Chron C5A, or 12.5 Ma in the present GPTS (Andreescu 1981, Table 2).

Geochronological arguments in favour of a 10 Ma hipparion datum come from Turkey and Pakistan. In Turkey, continental biostratigraphy is based originally on pollen-zones (*pollenbilder*) that were identified during a lignite resource study (Sickenberg *et al.* 1975). The Yeni-Eskihisar pollen zone comes from paludal sediments with sparse mid-Miocene small mammals and no hipparions among the few large-mammal remains; it is dated as young as 11.1 Ma. The next-youngest pollen zone, Kizilhisar, contains Turolian (not middle-Vallesian as initially stated) mammals at Kayadibi, which is bracketed by tuffs dated 9.1 and 7.95 Ma. Early

Vallesian (MN-9) large-mammal faunas, with an hipparion and *Anchitherium*, are found, at Esme-Akcaköy, in fluvial sediments with no pollen and no radiometric ages. If one assumes that the Esme-Akcaköy early Vallesian levels must lie *between* the Yeni-Eskihisar and Kizilhisar pollen zones, a 12.5 Ma hipparion datum is hard to justify. Fortunately, Benda & Meulenkamp (1979) have found both Yeni-Eskihisar and Kizilhisar pollen spectra in lowermost Tortonian pelagic sections of the Aegean. The Yeni-Eskihisar zone occurs on the island of Zakynthos in the lower Tortonian (overlap of lower Zone N16, and Zone CN7; see Fig. 2), while the Kizilhisar zone is found in a number of other lower N16 associations, including that of Kastellios with its mid-Vallesian mammals. The authors concluded that the two pollen zones meet in lower N16, a level which we show (Fig. 2) at c.9 Ma, and are consistent with the Turkish ages. Evidently, the mid-Vallesian (Kastellios) is equivalent to early Kizilhisar pollen assemblages, and early Vallesian (Esme-Akcaköy) is time-equivalent to the upper Yeni-Eskihisar pollen zone. The absence of hipparion remains from 11 Ma swamp deposits in Turkey with Yeni-Eskihisar pollen could be due to taphonomical or ecological bias.

In the richly-fossiliferous and well-correlated Siwaliks Series of Pakistan and India (see below), the oldest hipparions are found in normal-polarity beds that clearly belong to lower Chron C5N (Anomaly 5 equivalent), at about 10 Ma (Barndt *et al.* 1978; Tauxe 1979; Barry *et al.* 1982, corrected for the present GPTS). This very well-documented palaeomagnetic 'call' (Johnson *et al.* 1982; Tauxe & Opdyke 1982) has impressed some colleagues as a better standard for calibrating the Old World hipparion datum than the motley assortment of radiometric ages and stratigraphic relationships alluded to in support of the 12.5 Ma datum. The Siwaliks have a fossil mammal fauna that is more equatorial in its relationships than temperate, however, and it is not possible at present to identify a definitive Vallesian assemblage in association with the Siwaliks datum. Instead, MacFadden & Woodburne (1982) have concluded that the earliest Siwaliks hipparion is a *Cormohipparion* without the derived characters of the Vallesian '*primigenium*/Type 1' taxon, and which descended directly from *C. sphenodus*-like ancestors in an independent, south-Eurasian lineage. Its first appearance at c.10 Ma in the Nagri faunas would therefore be irrelevant to the time of arrival of other hipparions north and west of the Himalayas.

We note, in passing, that the Siwaliks may have the only *Cormohipparion* in the Old World. If genoholotype *Hipparion prostylum* is set on a separate phylogenetic line from the '*primigenium*/Type 1' taxon (MacFadden & Skinner 1982), the genus *Hippotherium* Kaup 1836, genoholotype *Equus primigenius* von Meyer 1829, is thereby restored, and takes priority over *Cormohipparion* as the name for some, at least, and perhaps all early Vallesian hipparions in the temperate regions of the Old World.

Equus datum

The magnetostratigraphy in superposed faunal sequences of Anza-Borrego (California) and San Pedro Valley (Arizona) document the evolution of *Equus* in middle Blancan faunas in the short normal-polarity zone of the middle Gauss Chron (Johnson *et al.* 1975; p. 325; Opdyke *et al.* 1977) at about 3.1 Ma in the time-scale of this paper, and in good agreement with North American dating of Middle Blancan (Fig. 3).

The immigration of *Equus* in Europe occurs within the MN16b interval of Mein (1979), typified in the Montopoli level of the Val d'Arno (Azzaroli 1977) and bounded by the Etouaires and Roccaneyra local faunas (southern France) near its beginning and end, respectively. Dating of these and other French continental Pliocene sites (Bout 1975; Bandet *et al.* 1978) suggests that MN-16b spans 3.0–2.5 Ma, in round numbers. Lindsay *et al.* (1980) cite evidence that *Equus* did not enter Eurasia until *c.*2.6 Ma, and so far it has been conclusively identified only in the Roccaneyra collection.

MN-16b assemblages, with earliest *Equus*, are found at the base of the Khaprovian 'faunal complex' of the eastern Parathethys (Black Sea–Caspian–Aral basins) according to Gabunya (1981). In the USSR, Lower Khaprovian correlates to upper Akchagylian Stage (Gabunya 1981), and in Romania the Khaprovian fauna is identified with the upper Romanian Stage (Andreescu 1981). Both of these stages begin in the upper Gauss (cf. Andreescu 1981), and the *Equus* datum is therefore somewhat younger, e.g. near the upper limit of the Gauss.

MN-16b assemblages cannot be identified in the Siwaliks, which have an endemic fauna, but the first *Equus* in this region is generally associated with the Tatrot-Pinjur 'stage' boundary. In their study of the Pinjur type section in India, Azzaroli & Napoleone (1981) place this boundary at the base of the Kansal Formation, and locate it in the uppermost Gauss (*c.*2.6 Ma in the present GPTS). Barry *et al.* (1982), working in Pakistan on the Tatrot type area, identified the earliest *Equus* slightly lower in the Upper Gauss normal subzone (Opdyke *et al.* 1982) (*c.*2.8 Ma in the present GPTS), and stratigraphically below tuffs in the lowermost part of the Matuyama magnetozone dated at 2.53 Ma (Johnson *et al.* 1982).

In Africa, the arrival of *Equus* is apparently influenced by ecological barriers. In the equatorial drylands of the Rift Valley, the evidence is unequivocal that *Equus* is not found at levels older than 1.9 Ma. The first *Equus* remains occur synchronously at the base of Bed I Olduvai, in collecting unit

3 below the KBS Tuff at Koobi Fora, and in level G at Shungura (Churcher & Richardson 1978), all of which are dated *c.*1.9 Ma and are correlated to the early Matuyama just below the Olduvai Subchron (Drake *et al.* 1980). The undated 'Equus Tuff' in the Awash Valley sequence of Ethiopia is apparently another example of the datum, but Kalb *et al.* (1982) have correlated it to East African faunal levels of about 1.0 Ma.

North America

The standard North American regional land-mammal ages, comprehensively dated by Evernden *et al.* (1964), have recently been reviewed by Tedford *et al.* (1983) to take account of the new information, and new analytical standards, of the 20 years that have passed since that virtually indestructible study. In this context we have included marine–nonmarine 'tie points' in central Florida (Webb *et al.* 1978; MacFadden & Webb 1982) and the Florida Gulf Coast (Hunter & Huddleston 1982), which support and amplify the 'Barstovian-Orbulina' correlation in the Texas coastal plain proposed by R. H. Tedford years ago (see Van Couvering & Berggren 1974).

Direct palaeomagnetic profiling in North American (and South American) mammal-bearing sequences generally has been used to refine K-Ar age calibration estimates, not the other way around. The synthesis of North American mammal biochronology, however, gives a more accurate control for the palaeomagnetic stratigraphy than direct K-Ar age determinations on the local stratigraphy. In the Rio Grande graben, for instance, MacFadden (1977) used local fission-track dates to place the Upper Chamita l.f. within the lower reversed-polarity subchron of the Gilbert, at *c.*5.0 Ma. Tedford (1981) pointed out that this was too young for late Hemphillian (Coffee Ranch equivalent) mammals, and suggested that the correct 'call' would be to the lower part of Chron 6, at *c.*6.5 Ma, in view of the more extended magnetostratigraphy of Rio Grande strata, subsequently obtained by

TABLE 2 Calibration of California benthic zones. Sources: (1) Obradovich & Naeser 1981. (2) Poore *et al.* 1981. (3) Rowell 1981. (4) Keller & Barron 1981. (5) Poore, McDougall *et al.* 1981. (6) Crouch & Bukry 1979; Arnal 1980. (7) This paper. For the correlation of *Stichocorys peregrina* FAD see Weaver *et al.* 1981. For the palaeomagnetic correlation of the diatom zones see Barron 1981. Note:^a This date refers to the correlation by Armentrout & Echols 1981, Fig. 9, of lower Saltos Shale (near base Relizian in ref. 5 above) to Tranquillon Volcanics. *indicate direct K-Ar dating, (=) is GPTS calibration.

Base of:	Dated (1)	Correlated to:
<i>Bolivina obliqua</i> zone	close to *6.9 (Palos Verdes)	<i>S. peregrina</i> FAD, = 7.0 (1) <i>N. reinholdii</i> FAD, = 6.8 (2)
Middle Mohnian (mid <i>B. hughesi</i> zone)	*7.8 (stratotype)	<i>T. antiqua</i> FAD, = 8.8 (3)
Lower Mohnian	over *11.5 (stratotype) *14.6 (Caliente Rge)	mid- <i>C. miopelagicus</i> CN5a, = 14.5 (2) common <i>D. hustedtii</i> , = 14.0 (4)
Luisian	over *16.5 (Caliente Rge)	<i>S. hetermorphus</i> CN4, = 17.0 (5) lower <i>D. lauta</i> 'a', = 16.2 (5)
Relizian	*17.5 ^a (Tranquillon)	?up. <i>S. belemnos</i> CN2, = 17.8 (5) base <i>H. ampliaptera</i> CN3, = 17.6 (6)
Saucesian	*23, avge.	lwr. <i>C. abisectus</i> CN1a, = 23.4 (2, 7)

Barghoorn (1981). Similarly, May & Repenning (1982) used the biochronological synthesis to control the palaeomagnetic 'call' on the Warren, Mt. Eden, and Yepomera local faunas. At Anza-Borrego and in the San Pedro Valley, likewise, Opdyke *et al.* (1977) reasoned from biochronological considerations to identify the palaeomagnetic reversals observed in relation to Middle Blancan–Irvingtonian faunal sequences containing the *Equus* datum (see above), although this again is hardly a test of the internal calibration of the GPTS.

In California coastal basins, a number of mammalian local faunas have been related to marine biostratigraphy in relatively intimate stratigraphic sequences, locally with radiometric control. Savage & Barnes (1972) summarized Miocene marine-nonmarine correlations in a general way, but without correlating the marine sequence to global planktonic microfossil zonation. In view of somewhat more detailed lithostratigraphic studies of the fossiliferous units, as presented by Armentrout & Echols (1981; see also Tedford *et al.*, in press, who adopt the same correlations), and recent revisions to dating and correlation of the California benthic zones to which the mammals are directly related, it is possible to show second-order tie-ins between North American land mammal biochronology and the standard marine microfossil zonation that appear to be relatively sturdy and reliable.

The sequence of California benthic foraminifera stages of Kleinpell, with which the mammal localities have been directly correlated, is now known to overlap and gap over major intervals. Dating by Obradovich & Naeser (1981) confirmed that the type Delmontian Stage, near San Francisco, is the same age as the lower part of the type Mohnian, in Los Angeles, and that the '*Bolivina obliqua*' beds overlying the type Mohnian are therefore not Delmontian but an unassigned, latest Miocene interval. Studies of the California benthic stage faunas associated with planktonic zones in the traditional onshore sections and in offshore cores also indicate considerable overlap, at least in some of the nominally characteristic taxa (Crouch & Bukry 1979; Arnal 1980). The planktonic zonal correlation of the definitive lower limits of each successive stage indicate a GPTS calibration of the sequence that is systematically older than the K-Ar calibration of Turner (1970), but more in line with that indicated by Obradovich & Naeser (1981). The mammal 'tie points' (Appendix III) refer to this new calibration.

South America

K-Ar calibration of the South American land mammal ages is based, so far, on too few dates to adequately test the direct GPTS correlations that have been made on mammal-bearing beds (Marshall *et al.* 1979; Marshall *et al.* 1982; Marshall *et al.* 1983). Also, there are no published correlations between the mammalian and marine microfossil biostratigraphy.

Europe (and North Africa)

In Western Europe and the Mediterranean basin, little has been added to the marine-nonmarine correlations cited in our earlier studies (Van Couvering & Berggren 1977; Berggren & Van Couvering 1978), with regard to Portugal, southern Spain, the Rhone Valley, Tuscany, and Tunisia; we must regard the Rierussa (Valles-Penedes, Barcelona) and Gebel Zelten (Libya) ties as unconfirmed awaiting further study. However, at Bou Hanifia (Ouda & Ameer 1978) and at

Kastellios (Bruijn & Zachariasse 1979), follow-up studies have strengthened the marine-nonmarine correlations, and Benda & Meulenkamp (1979) have added a new dimension with trans-facies correlation of pollen zones in the Aegean.

With regard to Early Miocene marine-nonmarine correlations, the classical Aquitanian-Burdigalian-Helvetian equation in SW France has been superseded, perhaps only temporarily, by evidence from the Tajo Basin sequence in Portugal and from the central Paratethys sequence, where direct stratigraphic correlations have been adduced between MN-zones and marine microfossil zones. Current data on the calcareous nannoplankton of the Paratethys sequence suggests strongly that the calibration ages that we proposed earlier for early Miocene mammal history in western Eurasia (Van Couvering & Berggren 1977) are too young, and should be revised older in accordance with the GPTS calibration of the correlated marine microfossil zones.

The calibration of the early Miocene mammal biochronology of Europe and North Africa below MN-5 obviously depends more on correlation to the GPTS than on internal K-Ar dating, and for this reason the early Miocene 'tie points' in the correlation matrix do not prove anything.

The modification suggested for the continental time-scale is of considerable interest in terms of mammalian biogeography and biochronology. It shows that MN-3b, the time of African immigration and the closing of the Tethys in the Zagros zone, begins at 20 Ma or slightly earlier, not *c.*16 Ma (Van Couvering & Berggren, 1977). In the Tajo faunas, the marine correlation of Lisboa IVb is estimated from the FAD of *Gds. altiapertura* in directly underlying beds, and the presence of *Praeorb. sicana* in directly overlying beds (Antunes *et al.* 1973), although this biostratigraphy is currently being resampled (L. Ginsburg, pers. comm. 1983). On the Paratethys side, the absence of *D. druggii* from upper Eggenburgian samples has been taken as evidence of 'NN3' (CN2) age (Horvath & Nagymarosy 1979), while planktonic foraminifera suggest that upper Eggenburgian is in Zone N5 (Papp 1981, *et auctt.*). Rögl *et al.* (1979) point out that both upper Eggenburgian and Ottnangian exhibit cool-regressive lignitiferous continental facies which are very hard to distinguish without biostratigraphic control. Within this lignitiferous sequence is the only well-dated unit in the European early Miocene, the 'Lower Rhyolite' of Hungary, at 19.6 Ma (Hamor *et al.* 1979; the 21.5 Ma given by Vass 1979, is a preliminary figure). Its conventional assignment to basal Ottnangian without faunal evidence is clearly open to question (Vass 1979), and it is here tentatively referred to as upper Eggenburgian instead, as a provocative possibility.

Asia

In Asia, two regions have a well-developed mammalian biochronology: the Black Sea–Caspian–Aral depression, or 'Eastern Paratethys' of Neogene palaeogeography, and the Siwaliks–Salt Range in the Himalayan foothills. For reasons of space we do not treat Siberia, Mongolia, and China, where Neogene mammal biochronology is (as yet) not well dated, nor Japan and South-east Asia, where the mammal record is mostly Pleistocene.

The Asian biochrons shown on Fig. 3 are those of the Eastern Paratethys, as characterized and correlated by Gabunya (1981); for full faunal lists of the sites in the Black Sea basin see Dubrovo & Kapelist (1979). For the Miocene part, terminology follows the present consensus for 'regional

TABLE 3 Early Miocene correlation matrix in Europe. Tajo basin correlations (Antunes *et al.* 1973; Antunes 1979) estimated according to current standards. MN-zone assignments *vide* Mein (1975; 1979). Paratethys correlations for mammals by Rabeder & Steininger (1975) and Rabeder (1978), for planktonic microfossils from data in Horvath & Nagymarosy (1979), Báldi-Beke & Nagymarosy (1979), Rögl *et al.* (1979) and Lehotayova & Molčíkova (1978); Paratethys dating from Vass & Bagdasarjan (1978), Vass (1979), and Hámor *et al.* (1979). Dates with (*) are local K-Ar ages from the indicated stages; those with (=) are from GPTS calibrations. Abbreviations (b. m. u) for basal, and middle, and upper, respectively.

Correl.	Tajo Basin mammal faunas	Mammal zone	Cent. Paratethys mammal faunas	Correl.
—	—	MN-6	Neudorf-Sandberg (u. Baden. *15.0)	m-CN5a = 14.0
		MN-6	Kleinhadersdorf (m. Baden)	b-CN5a = 14.5
m-N.9? = 15.2	Qta. da Farinheira (Lisboa Vb)	MN-5	Neudorf-Spallte (b. Baden *16.5)	m-CN4, m-N.8 = 15.5
—	—	MN-4b	Eibiswald (Karpát *18, c.)	m-CN3, m-N.7 = 17.3
b-N.8? = 16.8	Qta. Pombeiro (Lisboa Va)	MN-4a	Orechov, Ipolytarnoc (Ottományian)	?CN2, u-N.6 = 17.8
b-N.6? = 19.0	Qta. do Narigao (Lisboa IVb)	MN-3b	Langau, Tuchorice (u. Eggenb.) (*19.6?)	CN2, m-N.5 = 20.5, c.
b-N.4? = 23.5	Horta das Tripas (Lisboa II)	MN-3A	Eggenburg (b. Eggenburgian)	b-CN1c, m-N.4 = 23.0
—	—	MN-1?	Linz (u. Egerian)	m-CP19b? = 25.0

stages' (Papp 1981), which in principle represent both marine and non-marine sequences (Steininger 1977). For the Pliocene and Pleistocene, however, we adopt the 'mammal ages' or 'faunal complexes' recognized by Soviet palaeobiologists (cf. Nikiforova 1977; Gabunya 1981) in place of the Kimmerian, Akchagylian, Apsheronian, and 'Pleistocene' stages. Unfortunately, Miocene 'faunal complexes' have not yet been defined for this region.

The early Miocene marine sediments in the deeper basins of the Eastern Paratethys are well-correlated to those of the Central Paratethys, and to this extent to the open-ocean zonation (Papp 1981). However, the vast sheets of shallow-water and epicontinental strata that spread out over the Ukrainian and Central Asian platforms beyond the deep basins are zoned primarily by endemic shallow-water mollusc faunas (Steininger & Rögl 1979). From the mid-Miocene Volhynian (= early Sarmatian of Central Paratethys) onwards, after the retreat of the Paratethys oceans to the Black and Caspian seas, the endemic molluscs provide the principal zonation in European and Central Asia (Steininger 1977; Andreescu 1981; Papp 1981).

The mollusc-bearing paludal and limnic strata of the Eastern Paratethys Neogene, in turn, are well suited to close correlation with mammal faunas, and also to surface-outcrop palaeomagnetic traverses. Furthermore, several K/Ar dates of mid to late Neogene age have been related, somewhat loosely, to the mollusc zonation (Vass & Bagdasarjan 1978), and at Saro, Eastern Georgia, dates of 10.0 and 10.6 Ma have been obtained in sequence with early Maeotian (early Turolian) mammals (Gabunya & Rubinstein 1977).

Andreescu (1981) reviewed dating, palaeomagnetic analysis,

and biostratigraphy in the western Black Sea (Dacian) basin. According to his Table 2, the first 'Néogène Supérieur-Mollusques' zone (NSM₁, *Abra reflexa*), in Volhynian (basal Sarmatian) strata, was most probably coincident with lower 'Chron 14' (the top of the major normal event of Chron C5AD, c.14 Ma in the present GPTS), and NSM₄, *Sarmatimactra bulgarica* Zone, in Khersonian (upper Sarmatian) strata, spans the earliest reversed part of Chron C5 (between 11.0 and 11.5 Ma). Gabunya (1981) placed late Volhynian mammals of the eastern Black Sea basin in MN-8, and Khersonian mammals in MN-10; these we have independently calibrated to 13.0 Ma and 10.5 Ma, respectively (Fig. 3), which compares fairly well with the apparent GPTS ages in the coeval mollusc zones. Another association of Khersonian molluscs and MN-10 mammals is described by Nicolas (1978) from the Küçükçekmece sites on the Sea of Marmora, near Istanbul.

Semenenko & Pevzner (1979) obtained palaeomagnetic measurements on mid- to late Miocene marine beds and on upslope shallow-water sections of the Black Sea basin that they interpreted as the record of Chron 7 to Chron 4. At the base of this section, polarities correlated the uppermost part of Chron 7 (c.7.0 Ma in age, in the present GPTS) are associated with an Upper Maeotian (Akmanaian) molluscan fauna characteristic of the NSM₆, *Congerina pantacapa* Zone of Andreescu (1981). The mammal faunas of the Upper Maeotian in this region are independently assigned to MN-13 (late Turolian) age (Gabunya 1981), which we date at c.6.8 Ma (Fig. 3). The 'MN-10' *D. neohamatus* - *D. neoerectus* nannoflora reported from this level (cf. Semenenko & Pevzner 1979) is apparently too old to be *in situ*, whereas the higher

marine beds have yielded NN-11 to NN-13 nannofloras associated with Chrons 6 to early 4, comparable to the standard deep-sea record.

According to Andreescu (1981) the base of the NSM₁₂, *Ebersiniania milcovensis* zone is within the late Gauss (Kaena) normal interval, and is well correlated to the Upper Romanian Stage of the Dacic Basin, and also to the Upper Akchagylian Stage of central Asia. Mammals found at these levels, both in the Slatina faunas of Romania (Feru *et al.* 1978) and the later Khaprovian complex of Transcaucasia (Gabunya 1981) correlate very closely to the mid-MN16b, Roccaneyra level. The GPTS age of the NSM₁₂ zone in the Ponto-Caspian (2.6 Ma) is in exact agreement with dating at Roccaneyra (see 'Equus Datum' above).

Siwaliks

Recent collecting in the classical Siwaliks sections of the Potwar Plateau has been carefully integrated with extensive palaeomagnetic profiling (Barry, *et al.* 1982; Johnson, *et al.* 1982; Tauxe & Opdyke 1982), such that four newly-established 'mammal zones' based on observed biostratigraphy can be tied directly to the GPTS (see Appendix III). These zones, in turn, are approximately equivalent in time to the Nagri, Dhok Pathan, Tatrot and Pinjor (Barry, *et al.* 1982), considered purely as biochrons divorced from formations.

The problem remains, as before, that the Siwaliks faunas are not easy to correlate to the dated mammalian biochronology in the temperate regions, because the region was part of the 'monsoonal' subtropical province extending from South-east Asia to Arabia and the African Sahel. In the discussion of the 'Hipparion Datum', we have explained why we assign the early Nagri, represented in the rocks by the base of Barry *et al.*'s (1982) 'Hipparion s. 1.' zone in lower Chron C5N, to latest Vallesian or earliest Turolian time. Also, in the discussion of the 'Equus Datum', we have noted that the first occurrence of *Equus* in the lower part of the '*Elephas planifrons*' zone, in the late Gauss (Azzaroli & Napoleone 1981; Barry *et al.* 1982) identifies the beginning of the Tatrot biochron with mid-Villafranchian, middle MN-16b.

The beginning of the Dhok Pathan biochron can be defined by the immigration of *Selenoportax lydekkeri*, the nominative taxon for the second of the new Siwaliks zones (Barry *et al.* 1982). The lowest remains of *Selenoportax* appear in the middle of Chron 8 (present notation) at a level dated to c.7.6 Ma in the present GPTS. The extinction of *Deinotherium* and the appearance of large giraffids in the earliest part of this zone correlate to the middle of MN-12, just above the level of Samos (c.8.0 Ma, re-dated *file* N. Solounias), which has *Selenoportax*, *Deinotherium* and *Helladotherium* (Solounias 1981), but below Maragheh (7.4 Ma–7.0 Ma: Campbell, *et al.* 1980), as well as Los Mansuetos, from which no deinotheres have been reliably documented.

The Tatrot land-mammal age begins with the immigration into the Siwaliks area of the hippopotamus *Hexaprotodon sivalensis*, the nominate taxon for the third Siwaliks zone of Barry *et al.* (1982). The first remains of *Hexaprotodon* occur here in a zone of normally magnetized strata assigned to the upper normal interval of Chron 5 (5.4 Ma in the present GPTS). In SW Europe, hexaprotodonts similar to (or conspecific with) Siwaliks *Hexaprotodon* and those of early Kerian Wadi Natrun and Sahabi faunas (see Fig. 3) immigrated from Africa in latest MN-15 (e.g. at Casino, Alcoy and Venta del Moro) at the end of the Miocene, c.5.4 Ma. (cf.

Coryndon 1978; Azzaroli & Guazzone 1979). We assume, for the purpose of calibration, that the appearance of the genus in SW Europe was synchronous in the Siwaliks.

Africa

The Neogene fossil mammal record of Africa has excellent radiometric control, particularly in East Africa, but marine-non-marine correlations are few and generally not of good quality (Van Couvering & Van Couvering 1976). The best is at Bou Hanifia, Algeria (Ouda & Aneur 1978), where marine intercalations and a dated tuff can be related to a diverse Vallesian mammal fauna (see Appendix III). At Laangebaanweg, in Saldanha Bay, South Africa, and also at Sahabi, in Libya, poorly-dated early Kerian mammal faunas with transient 'northern tourists' such as bears and peccaries are preserved in geological settings that suggest end-Miocene backfilling of channels incised during Messinian sea-level decline (Hendey 1981), just as in southern Spain (Azzaroli & Guazzone 1979); the Rhone Valley (Clauzon, *et al.* 1982); and Bone Valley, Florida (MacFadden *et al.* 1981). Direct correlation to microfossil zones is missing, however, in the African sites, and tying these mammals to the latest Miocene at 5.4 Ma is based on the assumption that the Messinian regression has been correctly identified. Similarly, coeval North African large-mammal faunas, of late Kisingirian (or early Tinderetian?) age, c.16–15 Ma, at Jebel Zelten, Wadi Moghra, and Yeroham (Israel) may have been buried in coastal drainages that were backfilled during the mid-Miocene transgression whose culmination is associated with the *Orbulina* Datum, at c.15.0 Ma.

Palaeomagnetic measurements in Africa, including the studies at richly fossiliferous sites of Olduvai, Shungura, Hadar, and Koobi Fora, in East Africa, and Makapansgat in South Africa, are confined to the Pliocene and Pleistocene (see 'Equus Datum' above). Except for Makapansgat, these sequences are also directly dated and the question of comparing time-scales does not arise.

Postscript

In a recent paper on the magnetostratigraphy and K-Ar geochronology of basalts in north-west Iceland, McDougall *et al.* (1984) report an estimate of 11.1 Ma for the age of the older boundary of marine magnetic anomaly 5. However, the study of Tauxe *et al.* (1984) 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 of about 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 *et al.* (1985) conclude from this disparity, isotopic ages can have errors far greater than quoted analytical uncertainties, thereby 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 magneto-bio- and radiochronology.

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The preparation of a paper of this nature, attempting, as it does, to synthesize a large amount of data from a wide variety of sources — much of it as yet unpublished — requires the cooperation, to say nothing of the patience and indulgence, of many colleagues. We would like to express our sincerest gratitude to all those who have unselfishly aided us with published and unpublished data in the preparation of this paper. If we have appeared persistent or inquisitive at times it is only because we have tried to make this paper as comprehensive and well documented as possible so that it may serve as a standard in future studies of rates of geologic processes.

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Appendix I.

TABLE 4 Planktonic foraminiferal biostratigraphy near the Oligocene–Miocene boundary in some DSDP cores.

Site No.	LAD <i>opima</i>	FAD <i>kugleri</i>	FAD <i>primordius</i>	LAD <i>angulicosturalis</i>	FAD <i>dehiscens</i>	LAD <i>kugleri</i>	O/M Boundary & criterion (a)	Author
55			Mid-14 (125 m)		13/2 (114 m)	12/2 (105 m)	125 m (FAD <i>primordius</i>)	Krasheninnikov (Keller)
71	upper 46 (410 m)	top 39 (347 m)	base 36 (326 m)	—	—	top 31 (272 m)	345 m (FAD <i>kugleri</i>)	Beckmann
74	basal 6 (54 m)	mid-5 (47 m)	upper 5 (44 m)	—	—	lower 3 (25 m)	47 m (FAD <i>kugleri</i>)	
77B	—	basal 34 (318 m)	—	—	31/5 (289 m)	30/5 (277 m)		Jenkins & Orr (Keller)
149	in 29 (251 m)	base 25 (223 m)	base 25 (223 m)	—	in 21 (180 m)	22/6 (195 m)	223 m (FAD <i>primordius</i>)	Bolli
151	FAUNAL ASSOCIATIONS ONLY						311 m (LAD cf. <i>kugleri</i>)	& Premoli-Silva
171	INADEQUATE DATA							—
173	INADEQUATE DATA							—
214	—	24/5 (225 m)	24/1 (219 m)	—	23/2 (211 m)	23/2 (211 m)	219 m (FAD <i>primordius</i>)	McGowran
214	—	24/2 (222 m)	—	—	—	23/2 (211 m)	219 m (near FAD <i>kugleri</i>)	Berggren <i>et al.</i>
237		21/2 (189 m)	basal 19 (178 m)	—	17/2 (151 m)	19/5 (175 m)	178 m (FAD <i>primordius</i>)	Vincent
238	—	—	mid-47 (436 m)	—	—	top 63 (405 m)	mid-47 (FAD <i>primordius</i>)	

Table 4 continued.

Site No.	LAD <i>opima</i>	FAD <i>kugleri</i>	FAD <i>primordius</i>	LAD <i>angulifurcata</i>	FAD <i>dehiscens</i>	LAD <i>kugleri</i>	O/M Boundary & criterion (a)	Author
289		76/4 (717 m)	69/5 (654 m)	—	—	basal 65 (617 m)	654 m (FAD <i>primordius</i>)	Saito
292	lower 21 (193 m)	lower 17 (158 m)	basal 18 (168 m)	basal 18 (168 m)	—	basal 13 (121 m)	168 m (FAD <i>primordius</i>)	Ujje
296	—	—	36/3 (333 m)	—	mid-34 (313 m)	—	333 m (FAD <i>primordius</i>)	(Keller)
317B	mid-28 (853 m)	basal 25 (801 m)	basal 24 (782 m)	—	—	—	801 m (FAD <i>kugleri</i>)	Kaneps
354	9/10 (406– 453m)	—	mid-9 (400 m)	8/9 (349– 396 m)	7/8 (292 m)	—	400 m (FAD <i>primordius</i>)	
356	—	—	in 5 (90 m)	—	4/5 (66–85 m)	4/5 (66–85 m)	not determined (unconformity)	Boersma
357	18/3 (212 m)	14/15 (160– 170 m)	14/1 (152 m)	16/1 (190 m)	13/1 (132 m)	11/2 (105 m)	160–170 m (conc. range <i>primordius</i> & <i>kugleri</i> in 14)	
362	—	42/43 (767– 796 m)	42/43 (767– 796 m)	—	40/41 (710– 730 m)	42/43 (767– 796 m)	767–786 m (FAD <i>primordius-kugleri</i>)	Jenkins
363		lower 2 (58 m)	1/4 (37 m)	2 (55 m)	1/4 (37 m)	1/4 (37 m)	55 m (within conc-range of <i>primordius</i> & <i>kugleri</i>)	Toumarkine
448		in 10 (90 m)	—	in 11 (100 m)	—	top 6 (43 m)	not determined but FAD <i>kugleri</i> = in 10 (90 m)	
516F	8/1–130 (237 m)	5/1–110 (208 m)	10/1–100 (256 m)	4/1–110 (198 m)	4/1–110 (198 m)	4/1–110 (198 m)	208 m (FAD <i>kugleri</i>)	Berggren
522	21/2 (83 m)	17/3 (68 m)	15/3 (59 m)	—	15/2 (57 m)	—	56–58 m (FAD <i>G. dehiscens</i>)	Poore

TABLE 5 Calcareous nannoplankton biostratigraphy near the Oligocene–Miocene boundary in some DSDP cores.

Site No.	LAD <i>H. recta</i>	LAD <i>S. ciproensis</i>	LAD <i>Z. bijugatus</i>	LAD <i>R. bisecta</i>	LAD <i>R. hesslandii</i>	LAD <i>C. abisectus</i>	FAD <i>D. druggii</i>	NP25/NN1 or equivalent	Oligocene–Miocene boundary	Author
55	I N A D E Q U A T E D A T A									
71	20-cc (180 m)	39-cc (350 m)		41 cc (372 m)		36–6, 63 (325 m) (Bukry)	30-cc (270 m)	LAD <i>R. bisecta</i> (372 m)	LAD <i>R. bisecta</i> (372 m)	Haq & Lipps
74	10–1 (82 m)	6–1,140 (47.40 m)		6–1,140 (47.40 m)			3-cc (27 m)	LAD <i>R. bisecta</i> & <i>S. ciproensis</i> (47.40 m)	LAD <i>R. bisecta</i> (47.40 m)	Haq & Lipps
77B		37–4,65 (343 m)		37–4,65 (343 m)		34–4,66 (313 m)	33–4,63 (304 m)	LAD <i>R. bisecta</i> & <i>S. ciproensis</i> (343 m)	LAD <i>R. bisecta</i> (343 m)	Bukry

TABLE 5 continued

Site No.	LAD <i>H. recta</i>	LAD <i>S. ciproensis</i>	LAD <i>Z. bijugatus</i>	LAD <i>R. bisecta</i>	LAD <i>R. hesslandii</i>	LAD <i>C. abisectus</i>	FAD <i>D. druggii</i>	NP25/NN1 or equivalent	Oligocene-Miocene boundary	Author
149		27-3,73 (236 m)		27-3,73 (236 m)		27-2,66 (234 m)	23-4,59 (200 m)	LAD <i>S. ciproensis</i> & <i>R. bisecta</i> (236 m)	LAD <i>R. bisecta</i> & <i>S. ciproensis</i> (236 m)	Bukry
149	29-2,25 (252.75 m)	28-2,25 (242.75 m)		higher than 20-3,25 (171.75 m)			23-3,100 (199 m)	LAD <i>H. recta</i> (252.75 m)	LAD <i>H. recta</i> (252.75 m)	Hay & Beaudry
151		8-1, 81-82 (329.80 m)		4-2,25 (238.75 m)			4-2,141 (240 m)	LAD <i>S. ciproensis</i> (329.81 m)	LAD <i>S. ciproensis</i> (329.81 m)	Hay & Beaudry
161		3-5,38 (24.40 m)		5-cc (44 m)	3-5,38 (24.40 m)	3-2,120 (20.7 m)	2-5,114 (15 m)	LAD <i>S. ciproensis</i> & <i>R. scrippsae</i> (24.40 m)	between LAD <i>C. abisectus</i> & LAD <i>S. ciproensis</i>	Bukry
165A		2-1,114 (15.14 m)		2-3,85 (17.35 m)		top of hole below LAD <i>R. abisecta</i>	top of hole below FAD <i>D. druggii</i>	LAD <i>S. ciproensis</i> (15.14 m)	not recovered but at LAD <i>C. abisectus</i>	Roth
167		11-5,50 (303.50 m)		12-1,50 (334.5 m)		10-3,50 (263.5 m)		LAD <i>R. bisecta</i> (334.5 m)	LAD <i>C. abisectus</i> (263.5 m)	Roth
171		4-1,50 (64.5 m)		4-1,50 (64.5 m)	6-2,50 (104 m)	4-1,50 (64.5 m)	3-1,50 (46.50 m)	LAD <i>S. ciproensis</i> (64.5 m)	LAD <i>C. abisectus</i> , <i>S. ciproensis</i> , <i>R. bisecta</i> are simultaneous	Roth
173				35-1,115 (312 m)		34-1,143 (306 m)		LAD <i>R. bisecta</i> (312 m)	LAD <i>R. bisecta</i> (312 m)	Wise
214		24-2,2 (220.5 m)	24-2,2 (220.5 m)	25-cc (237 m)				LAD <i>S. ciproensis</i> (220.5 m)	LAD <i>S. ciproensis</i> (220.5 m)	Gartner
234				12-1,85 (181.3 m)		10-3,49 (165 m)	6-2,27 (77.75 m)	LAD <i>R. bisecta</i> (181.35 m)	LAD <i>R. bisecta</i> (165 m)	Roth
236		21-6,99 (195.5 m)		21-6,99 (195.5 m)	28-1,127 (254.77 m)	20-5,98 (184.5 m)	19-3,95 (172 m)	LAD <i>R. bisecta</i> & <i>S. ciproensis</i> (195.5 m)	LAD <i>C. abisectus</i> (184.5 m)	Roth
237	INADEQUATE DATA									
238		50-4,114 (467.65 m)		48-1,116 (444.16 m)		44-1,122 (406.22 m)	42-4,44 (389 m)	LAD <i>S. ciproensis</i> (467.65 m)	LAD <i>C. abisectus</i> (406.22 m)	Roth
289		79-1,60 (741.6 m)	90-3,126 (849.75 m)	92-1,120 (865.7 m)	91-1,120 (856.2 m)	57-2,30 (533.80 m)	72-3,30 (677.80 m)	LAD <i>S. ciproensis</i> (741.6 m)	undetermined	Shafik
292		18-3,40 (162 m)		18-3,40 (162 m)		17-1,126 (150.25 m)	14-2,40 (122.40 m)	LAD <i>R. bisecta</i> & <i>S. ciproensis</i> (162 m)	LAD <i>C. abisectus</i> (150.25 m)	Ellis

Table 5 continued.

Site No.	LAD <i>H. recta</i>	LAD <i>Z. ciproensis</i>	LAD <i>Z. bijugatus</i>	LAD <i>R. bisecta</i>	LAD <i>R. hesslandii</i>	LAD <i>C. abisectus</i>	FAD <i>D. druggii</i>	NP25/NN1 or equivalent	Oligocene-Miocene boundary	Author
296		38-1,96 (349.45 m)		38-1,96 (349.45 m)	48-1,140 (445 m)	34-1,98 (311.45 m)	33-1,105 (302 m)	LAD <i>R. bisecta</i> & <i>S. ciproensis</i> (349.45 m)	LAD <i>C. abisectus</i> (311.45 m)	Ellis
317B		26-2,95 (237 m)	34-1,30 (310.80 m)				20-cc (187 m)	LAD <i>S. ciproensis</i> (237 m)	LAD <i>S. ciproensis</i> (237 m)	Martini
354	10-3,85 (457.30 m)	9-cc (406 m)		10-1,73 (454.20 m)		9-1,73 (397.20 m)	8-1,61 (340 m)	LAD <i>S. ciproensis</i> (406 m)	LAD <i>S. ciproensis</i> (406 m)	Perch-Nielsen
356						3-2,72 (40.20 m)	4-cc (66.5 m)	unconformity	unconformity	Perch-Nielsen
357		15-cc (179.5 m)	14-cc (160.5 m)	14-cc (160.5 m)		10-cc (103.5 m)	10-1,65 (94.65 m)	LAD <i>S. ciproensis</i> (179.5 m)	LAD <i>S. ciproensis</i> (179.5 m)	Perch-Nielsen
362	41-3,10 (722.6 m)	44-cc (796 m)		41-cc (729.5 m)		33-cc (530.5 m)	40-cc (710.5 m)	LAD <i>S. ciproensis</i> (796 m)	FAD <i>D. druggii</i> (710.5 m)	Proto-Decima
363	2-2,10 (51.60 m)	2-cc (59.5 m)	1-4,101 (36.5 m)	1-cc (40.5 m)		1-2,60 (33.10 m)	1-cc (40.5 m)	LAD <i>H. recta</i> (51.60 m)	unconformity NN1 missing	Proto-Decima
386	4-4,93 (152.64 m)	4-4,93 (152.64 m)	11-cc (261 m)	4-5,80 (154 m)	5-1,80 (157.60 m)	4-4,93 (152.64 m)	4-5,80 (154 m)	LAD <i>R. scrippsae</i> (157.60 m)	between LAD <i>C. abisectus</i> & FAD <i>D. druggii</i> but undetermined	Thierstein & Okada
406	28-1,35 (255.35 m)		31-3,112 (287.60 m)			16-1,100 (142 m)		LAD <i>H. recta</i> (255.35 m)	LAD <i>H. recta</i> (255.35 m)	Muller
407	31-1,52 (283.5 m)		28-3,90 (258.4 m)	31-cc (291 m)	31-1,52 (283.5 m)			LAD <i>H. recta</i> (283.5 m)	LAD <i>H. recta</i> (283.5 m)	Steinmetz
407	43-cc (399 m)		30-1,44 (275 m)			18-3,10 (169.10 m)	21-cc (202 m)	LAD <i>Z. bijugatus</i> (275 m)	LAD <i>Z. bijugatus</i> + <i>D. enormis</i> (275 m)	Martini
445		45-cc (426.50 m)	43-cc (407.50 m)	41-6,42 (386.90 m)	41-3,42 (382.42 m)	33-cc (312 m)	41-1,42 (379.42 m)	LAD <i>S. ciproensis</i> (426.50 m)	FAD <i>D. druggii</i> (379.42 m)	Okada
448		10-2, 6 (83.1 m)	10-2,6 (83.1 m)			1-cc (5 m)	5-cc (24 m)	LAD <i>S. ciproensis</i> (83.1 m)	LAD <i>S. ciproensis</i> (83.1 m)	Martini
516F (516)	516-n 39-1,80 (136 m)	9-1,98 (246 m)	7-1,96 (220 m)	5-1,100 (208 m)		516-12-1 (47 m)	3-5,100 (198 m)	LAD <i>R. bisecta</i> (208 m)	LAD <i>R. bisecta</i> (208 m)	Aubry
522	—	15/16 (65 m)	—	15/2 (57 m)	15/3 (59 m)	15/2 (57 m)	14/2 (52 m)	LAD <i>R. scrippsae</i> + <i>R. bisecta</i> + <i>C. abisectus</i> (56-58 m)	LAD <i>R. scrippsae</i> + <i>R. bisecta</i> + <i>C. abisectus</i> (56-58 m)	Percival

Appendix II.

TABLE 6 Relationship of Neogene planktonic foraminiferal datum levels to observed magnetic polarity stratigraphy. Age estimates (Ma) derived from revised geomagnetic polarity time scale presented in this paper (Table 1). These data have provided the basic magnetobiochronologic framework for estimating the chronology of standard time-stratigraphic units and stage stratotypes.

Datum	Chron	Early Miocene		Ref.	Remarks	
		Magnetic polarity Chron and/or Anomaly	Correlative			Age (Ma)
1. FAD <i>Praeorbulina sicana</i>	C5C	mid-part of anom. 5C		16.6	2,3,6	ranges down to at least top of Chron C5CN in Site 521 (ref. 4)
2. FAD <i>Globorotalia miozea</i>	C5C	lower of 3 normal events of anom. 5C		16.8	2,6	
3. LAD <i>Globorotalia zealandica</i>	C5C	"		16.8	2	
4. LAD <i>Globorotalia pseudomiozea</i>	C5C	"		16.8	2	
5. FAD <i>Globorotalia birnageae</i>	C5C	base anom. 5C		17.0	2	
6. LAD <i>Catapsydrax Stainforthi</i>	C5C			17.4	2	
7. FAD <i>Globorotalia zealandica</i>	C5D	top anom. 5D		17.6	2	
8. FAD <i>Globorotalia pseudomiozea</i>	C5D	top anom. 5D		17.6	2	
9. LAD <i>Globorotalia semivera</i>	C5D	"		17.6	2	
10. LAD <i>Globorotalia incognita</i>	C5D	"		17.6	2	
11. LAD <i>Catapsydrax dissimilis</i>	C5D	"		17.6	2	
12. FAD <i>Globorotalia praescitula</i>	C5D	top anom. 5D		17.7	2	
13. LAD <i>Globoquadrina dehiscens</i> (f. <i>spinosa</i>)	C5D	between anom. 5D and 5E		18.3	2,3	observed in South Atlantic only to date.
14. FAD <i>Globigerinoides altiapertura</i>	C6A	top anom. 6A		20.9	2,3	
15. LAD <i>Globorotalia kugleri</i>	C6A	between base 6A and top unnumbered anomaly between 6A and 6B		21.8	2,3,6	
16. FAD <i>Globoquadrina dehiscens</i> (f. <i>spinosa</i>)	C6AA	anomaly between 6A and 6B		22.0	2,3	
17. LAD <i>Globoquadrina globularis</i>	C6B	anom. 6B		22.8	2	
18. FAD <i>Globoquadrina dehiscens</i>	C6B	between 6B and 6C		23.2	2-4,6	
19. FAD <i>Globorotalia incognita</i>	C6B	"		23.2	2,3	
20. LAD <i>Globigerina angulisuturalis</i>	C6B	"		23.2	2	
21. LAD <i>Globorotalia pseudokugleri</i>	C6B	"		23.2	2	
22. FAD <i>Globorotalia kugleri</i>	23 (=C6C)	mid-6C		23.7	2,6	recorded also between Chrons C6CN and C7 at Site 522 in South Atlantic (ref. 4) and Mediterranean region (ref. 5)
23. LAD <i>Globorotalia mendacis</i>	23 (=C6C)	"		23.7	2	

Early Miocene

Datum	Chron	Magnetic polarity Event and/or Anomaly Correlative	Age (Ma)	Ref.	Remarks
24. FAD <i>Globigerinoides primordius</i> (common)	C6C	just below 6C in reversed interval	24.3	2,3	
25. FAD <i>Globigerinoides primordius</i> (rare)	C7	anom. 7	25.8	2,3	

- Refs.: 1. Ryan *et al.* (1974)
 2. Berggren *et al.* (1983)
 3. Pujol (1983)
 4. Poore *et al.* (1982, 1983)
 5. Lowrie, Alvarez *et al.* (1982)
 6. Miller *et al.* (in press)

Middle Miocene

Datum	Chron	Magnetic polarity Event and/or Anomaly Correlative	Age (Ma)	Ref.	Remarks
1. LAD <i>Globorotalia siakensis</i>	C5	base anom. 5	10.4	1	
2. FAD <i>Globigerina nepenthes</i>	C5	just above 5A	11.3	1	identified between lower of two normal Subchrons interpreted as being in Chron 12 and top Chron 13 (ref. 2).
3. LAD <i>Globorotalia fohsi lobata</i> and <i>G. fohsi robusta</i>	C5	top 5A	11.5	1	
4. FAD <i>Globorotalia fohsi robusta</i>	C5A	normal Subchron, lower 5A	12.6	1	
5. FAD <i>Globorotalia fohsi lobata</i> .	C5AA	reversed Subchron, base 5AA	13.1	1	
6. FAD <i>Globorotalia praefohsi</i>	C5AC	normal Subchron, 5AC	13.9	1	
7. LAD <i>Globorotalia peripheroronda</i>	C5AD	lower part normal Subchron	14.6	1	
8. FAD <i>Globorotalia peripheroacuta</i>	C5B	normal Subchron, 5B	14.9	1.2	This is same taxon (i.e. datum level) as <i>G. fohsi</i> (no. 35) of ref. 2.
9. LAD <i>Praeorbulina sicana</i>	C5B	normal Subchron 5B	14.9	1	LAD <i>P. sicana</i> occurs in interval of no paleomagnetic data about 20 m above FAD <i>P. sicana</i> which occurs in anom. 5C correlative in Hole 516 (ref. 3).
10. LAD <i>Praeorbulina glomerosa</i>	C5B	normal Subchron 5B	14.9	1	Same remarks as above (9).
11. FAD <i>Orbulina suturalis</i>	C5B	anom. 5B	15.2	1,5	FAD <i>Orbulina</i> occurs in interval of no paleomagnetic data about 20 m above FAD <i>Praeorbulina sicana</i> which occurs in anom. 5C correlative in Hole 516F (ref. 3).
12. FAD <i>Praeorbulina circularis</i> .	C5C	top anom. 5C	16.2	1	sequential appearance of praeorbulinid taxa occurs in "normal" (DSDP Hole 563) and expanded (DSDP Hole 558) sequence of anomaly 5C correlative in North Atlantic (ref. 1)
13. FAD <i>Praeorbulina glomerosa</i>	C5C	near top 5C	16.3	1	occurs in Hole 516 about 15 m below FAD <i>Orbulina suturalis</i> in interval with no paleomagnetic data and about 5 m above FAD <i>P. sicana</i> in mid-part of Chron C5CN (ref. 3).
14. FAD <i>Globigerinoides diminutus</i>	(C5C)	(near top 5C)	16.3	3,4	see Remarks above (13).
15. FAD <i>Praeorbulina curva</i> .	C5C	mid-part anom. 5C	16.5	1	see Remarks under 12 above.
16. FAD <i>Praeorbulina sicana</i>	C5C	mid-part anom. 5C	16.6	1,3,4	ranges down to at least top of Chron C5C in Site 521 (ref. 5).

- Refs.: 1. Miller *et al.* (in press)
 2. Ryan *et al.* (1974)
 3. Berggren *et al.* (1983)
 4. Pujol (1983)
 5. Poore *et al.* (1982, 1983)

* (C5C) = not directly correlated to polarity interval but certainly within this interval based on bracketing data.

Late Miocene					
Datum	Chron	Magnetic polarity Event and/or Anomaly Correlative	Age (Ma)	Ref.	Remarks
1. LAD <i>Globoquadrina dehiscens</i>	GILBERT (4)	lowermost Gilbert	5.3	1-4	
2. LAD <i>Globorotalia linguaensis</i>		lowermost Gilbert	5.3	3,4	located in 'Epoch 7' in Site 519 (South Atlantic, ref. 8) but this interpretation is equivocal.
3. FAD <i>Globorotalia cibaoensis</i>	5	lowermost Gilbert	5.3	3,8	
4. FAD <i>Globorotalia margaritae</i>	5	mid-5 between events a and b	5.6	1,2,4,7	FAD usually recorded at or slightly above a level thought (by indirect correlation) to lie in basal Gilbert (4) Chron. Recorded by Saito (ref. 2) in RC-12-66 (Equatorial Pacific) and Pujol (ref. 4) in DSDP Hole 516A (Rio Grande Rise, South Atlantic) in Chron 5, and Cita (ref. 7) in DSDP Site 397 (off Cape Bajador, W. Africa). Recorded in basal Gilbert in Hole 502 (ref. 10).
5. FAD <i>Pulleniatina primalis</i>	5	anom. 3A	5.8	2	Indo-Pacific only. Recorded in mid-Chron 5 in Hole 503 (ref. 10).
6. <i>Neogloboquadrina acostaensis</i> (S to D)	5	anom. 3A	5.8	2,7	Suggested to have occurred in Mediterranean at a level younger than Gilbert/Chron 5 boundary = 5.3 Ma (ref. 11) but this may be due to misinterpretation of local (Cretan) paleomagnetic stratigraphy.
7. FAD dextral menardine Globorotaliids (= <i>G. menardii</i> form 5)	6	younger reversed interval	6.0	11	Mediterranean region. However, this may, in fact, be within Chron 6R (early part) if Cretan magnetic stratigraphy has been misinterpreted (see text for further discussion).
8. <i>Neogloboquadrina acostaensis</i> (D to S)	6	just below chron 5/6 boundary	6.1	2	
9. FAD <i>Globorotalia conomiozea</i>	6	younger reversed interval	6.1	5,6	Recorded in Crete from reversed interval of Chron 5 at 5.6 Ma (ref. 11). However, this may be due to misinterpretation of Cretan magnetostratigraphy (see text for further discussion).
10. LAD sinistral menardine Globorotaliids (<i>G. menardii</i> form 4)	6	early reversed interval near base Chron 6	6.6	11	This group includes <i>G. miozea</i> s.l. of Berggren (1977) which showed correlative disappearance at Rio Grande Rise in late Miocene. The exit level in Crete may actually lie within Chron 7 (rather than 6) if the Cretan magnetostratigraphy has been incorrectly identified (ref. 11) (see text for further discussion).
11. FAD <i>Neogloboquadrina humerosa</i>	8	reversed interval between 4 and 4A	7.5	6	Chron 8 of ref. 6 is reinterpreted to lie between anomalies 4 and 4A accounting for younger age estimate. Recorded in Sidufjall (C2) Subchron of Gilbert Chron (c.4.7 Ma) in Pacific (ref. 2) and eastern Atlantic (ref. 7) areas.
12. FAD <i>Neogloboquadrina acostaensis</i>	11	lower anom. 5	10.2	9	identified in normal Subchron identified as occurring in mid-Chron 10 in stratotype Tortonian (ref. 6).

Refs.: 1. Berggren (1973)
 2. Saito *et al.* (1975)
 3. Berggren *et al.* (1983)
 4. Pujol (1983)
 5. Kennett & Watkins (1974)
 6. Ryan *et al.* (1974)
 7. Mazzei *et al.* (1979)
 8. Poore *et al.* (1983)
 9. Miller *et al.* (in press)
 10. Keigwin (1982)
 11. Langereis *et al.* (1984)

Early Pliocene

Datum	Chron	Magnetic polarity Chron and/or Anomaly Correlative	Age (Ma)	Ref.	Remarks
1. LAD <i>Pulleniatina</i> <i>primalis</i>	G	reversed interval, latest Gilbert	3.5	9	Pacific Ocean only
2. <i>Pulleniatina</i> (S to D coiling change)	I L	just above Cochiti Subchron (a)	3.8	2,9	Recorded above Nunivak Subchron at level which should be equivalent to Cochiti Sub- chron (but not observed) on Fiji (ref. 10).
3. LAD <i>Globigerina</i> <i>nepenthes</i>	B E	top Cochiti Subchron (a)	3.9	1-4,8	Same as above.
4. LAD <i>Pulleniatina</i> <i>spectabilis</i>	R T (4)	top Cochiti Subchron (a)	3.9	1	Indo-Pacific only; FAD <i>P. spectabilis</i> recorded at Site 503 (eastern Pacific) at about 4 Ma but this is a lone occurrence and probably not a true FAD (ref. 9).
5. FAD <i>Globorotalia</i> <i>crassaformis</i> s.s.	G I	within Cochiti (a) and Nunivak (b) combined	4.1	3	
6. FAD <i>Globorotalia</i> <i>crassaformis</i> s.1.	L B	just above Sidufjall (C ₁) Subchron	4.3	3-4,9	
7. LAD <i>Globigerinoides</i> <i>seiglei</i>	E R	just above Sidufjall (C ₁) Subchron	4.3	3,4,8	LAD <i>G. seiglei</i> observed in Hole 502 (Caribbean) within Thvera Subchron (ref. 9).
8. FAD <i>Globorotalia</i> <i>puncticulata</i>	T	Sidufjall (C ₁) Subchron	4.4	3-5,8	
9. LAD <i>Globorotalia</i> <i>cibaoensis</i>	(4)	Sidufjall (C ₁) Subchron	4.4	3,6	
10. FAD <i>Sphaeroidinella</i> <i>dehiscens</i> .	G I	middle of lower reversed Gilbert	5.1	1,2	Recorded at various levels in Holes 502 and 503 in basal Gilbert depending on sample intervals (ref. 9).
11. FAD <i>Globorotalia</i> <i>tumida</i>	L	lower reversed Gilbert	5.2	2,9	Predominantly Indo-Pacific; recorded in Caribbean Hole 502 also (ref. 9).
12. FAD <i>Pulleniatina</i> <i>spectabilis</i>	B	lower reversed Gilbert	5.2	1,2	Indo-Pacific only
13. FAD <i>Globigerinoides</i> <i>conglobatus</i>	E	lowermost Gilbert	5.3	3,4,6	
14. FAD <i>Globorotalia</i> <i>cibaoensis</i>	R	lowermost Gilbert	5.3	3,6	
15. LAD <i>Globoquadrina</i> <i>dehiscens</i>	T (4)	lowermost Gilbert	5.3	1-4	Recorded near base (just below) Sidufjall Subchron on Fiji (ref. 10).
16. LAD <i>Globorotalia</i> <i>lenguaensis</i>	(4)	lowermost Gilbert	5.3	3,4	

Refs.: 1. Hays *et al.* (1969)
2. Saito *et al.* (1975)
3. Berggren *et al.* (1983)
4. Pujol (1983)
5. Mazzei *et al.* (1979)

6. Poore *et al.* (1983)
7. Ryan *et al.* (1974)
8. Leonard *et al.* (1983)
9. Keigwin (1982)
10. Rodda *et al.* (in press)

Late Pliocene					
Datum	Chron	Magnetic polarity Chron and/or Anomaly Correlative	Age (Ma)	Ref.	Remarks
1. FAD <i>Globorotalia truncatulinoides</i> .	G	just below Olduvai event (= anom. 2)	1.9	1-6,9,10	
2. LAD <i>Globorotalia exilis</i>	A	Reunion event	2.1	3-6	Atlantic Ocean only
3. LAD <i>Globorotalia miocenica</i>	U	just below Reunion event	2.2	3-6,9	Atlantic Ocean only
4. (local) reappearance of <i>Pulleniatina</i>	S	just below Reunion event	2.2	2,10	Atlantic Ocean only
5. LAD <i>Globorotalia pertenuis</i>	(3)	top Gauss normal	2.5	10	Recorded in Caribbean (Site 502) and Pacific (Site 503) (ref. 10).
6. LAD <i>Globorotalia multicamerata</i>	G	between Kaena and Mammoth	2.9	3,4,9	
7. LAD <i>Globoquadrina altispira</i>	A	between Kaena and Mammoth	2.9	1-4,7,9	
8. FAD <i>Globigerinoides fistulosus</i>	U	between Kaena and Mammoth	2.9	1	
9. LAD <i>Sphaeroidinellopsis</i> spp.	S	top Mammoth event	3.0	1-4,7,9	
10. FAD <i>Sphaeroidinella dehiscens</i> s.s.	S	Mammoth event	3.0	1-4,9	
11. FAD <i>Globorotalia inflata</i>	(3)	Mammoth event	3.0	3,4	
12. LAD <i>Globorotalia conomiozea</i>		Mammoth event	3.0	3	
13. FAD <i>Globorotalia tosaensis</i>	M	just below Mammoth	3.1	1	
14. FAD <i>Globorotalia crassula</i>	A	just below Mammoth	3.1	3	
15. (local) LAD <i>Pulleniatina</i>	T	between Mammoth and Gauss/Gilbert boundary	3.3	2,10	Atlantic Ocean only
16. FAD <i>Globorotalia pertenuis</i>	U	between Mammoth and Gauss/Gilbert boundary	3.3	10	Recorded in both Caribbean (Site 502) and Pacific (Site 503) (ref. 10).
17. FAD <i>Globorotalia miocenica</i>	Y	between Mammoth and Gauss/Gilbert boundary	3.4	3,4,7	Atlantic only
18. LAD <i>Globorotalia margaritae</i>	A	between Mammoth and Gauss/Gilbert boundary	3.4	2	LAD recorded in reversed interval, just below Gauss/Gilbert boundary in Hole 502 (Caribbean Sea) (ref. 10).
	M	Gauss(4)/Gilbert(5) boundary			
	BERT				
	(4)				

- Refs.: 1. Hays *et al.* (1969) 6. Berggren *et al.* (1980)
 2. Saito *et al.* (1975) 7. Mazzei *et al.* (1979)
 3. Berggren *et al.* (1983) 8. Poore *et al.* (1983)
 4. Pujol (1983) 9. Leonard *et al.* (1983)
 5. Haq *et al.* (1977) 10. Keigwin (1982)

Pleistocene					
Datum	Chron	Magnetic polarity Chron and/or Anomaly Correlative	Age (Ma)	Ref.	Remarks
1. LAD <i>Globoquadrina pseudofoliata</i>	B R	$\delta^{18}\text{O}$ stage 7	0.22	1,2	
2. LAD <i>Globorotalia tosaensis</i>	U N H	lower Brunhes	0.6	5	
3. FAD <i>Pulleniatina finalis</i>	E S	midway between Jaramillo and Olduvai Subchrons	1.3	3,4	
4. LAD <i>Globigerinoides fistulosus</i>	M A	just above Olduvai Subchron	1.6	2-4	
5. LAD <i>Globigerinoides obliquus extremus</i>	T U Y A	Olduvai Subchron (anom. 2)	1.8	2,5,6	
6. FAD <i>Globorotalia truncatulinoides</i>	M A	just below base Olduvai	1.9	2-4,6	

- Refs.: 1. Thompson & Saito (1974)
 2. Berggren *et al.* (1980)
 3. Hays *et al.* (1969)
 4. Saito *et al.* (1975)
 5. Thompson & Sciarillo (1978)
 6. Keigwin (1982)

Appendix II

TABLE 7 Relationship of Neogene calcareous nannoplankton datum levels to observed magnetic polarity stratigraphy. (Further explanation as in Table 6.)

Early Miocene					
Datum	Chron	Magnetic polarity Chron and/or Anomaly Correlative	Age (Ma)	Ref.	Remarks
1. LAD <i>Helicosphaera ampliaperta</i>	C5C	top anom. 5C	16.2	5	located at base Chron C5CN in Hole 516 (ref. 1).
2. FAD <i>Sphenolithus heteromorphus</i>	C5C	just below anom. 5C	17.1	1	
3. LAD <i>Sphenolithus belemnos</i>	C5C	reversed interval just above 5D	17.4	1	indirectly correlated to Chron C5D-C5E boundary elsewhere (see ref. 3).
4. FAD <i>Sphenolithus belemnos</i>	C6A	mid-part anom. 6A	21.5	5	observed in early part of Chron C5DN in Hole 516 (ref. 1).
5. FAD <i>Discoaster druggi</i>	C6C	between anom. 6B and 6C	23.2	1,2,5	
6. LAD <i>Reticulofenestra bisecta</i>	23 (=C6C)	anom. 6C	23.7	1,2	LAD <i>R. bisecta</i> recorded between Chron C6C and C7 in Mediterranean (ref. 4).
7. LAD <i>Reticulofenestra scrippsae</i> (= <i>hesslandi</i>)	23 (=C6C)	anom. 6C	23.7	2	
8. LAD <i>Reticulofenestra abisecta</i>	23 (=C6C)	anom. 6C	23.7	2	May be local LAD inasmuch as this taxon is reported elsewhere at levels as high as middle Miocene; LAD <i>abisecta</i> recorded just below Chron C6CN in Mediterranean (ref. 4).

- Ref.: 1. Berggren *et al.* (1983)
 2. Poore *et al.* (1982, 1983)
 3. Ryan *et al.* (1974)
 4. Lowrie, Alvarez *et al.* (1982)
 5. Miller *et al.* (in press)

Middle Miocene

Datum	Chron	Magnetic polarity Chron and/or Anomaly Correlative	Age (Ma)	Ref.	Remarks
1. FAD <i>Catinaster coalitus</i>	11 (C5)	reversed interval below 5	10.8	1	range of <i>C. coalitus</i> restricted to Chron C5N in Hole 519 (initial occurrence several meters above contact with basement; ref. 2) and 521A (ref. 4).
2. LAD <i>Cyclococcolithus floridanus</i>	C5A	top anom. 5A	11.6	1	LAD of <i>C. floridanus</i> often used as surrogate criterion for NN6–NN7 boundary. However, <i>C. floridanus</i> occurs within Zone NN7 as defined by the FAD of <i>D. kugleri</i> in some areas, including Holes 558 and 563 (ref. 1).
3. FAD <i>Discoaster kugleri</i>	C5AB	within interval of C5AA–C5AB	13.1 ca.	1	FAD of <i>D. kugleri</i> not precisely located in 558 and 563. NN6–NN7 boundary arbitrarily drawn between C5AA and C5AB in figure 2.
4. FAD <i>Triquetrorhabdulus rugosus</i>	C5AC	base normal Subchron, 5AC	14.0	1	
5. LAD <i>Sphenolithus heteromorphus</i>	C5AD	normal event, 5AD	14.4	1	LAD occurs at essentially same level as FAD <i>Orbulina suturalis</i> in interval of no paleomagnetic data about 20 m above Chron C5CN in Hole 516 (ref. 3).

- Ref.: 1. Miller *et al.* (in prep.)
 2. Poore *et al.* (1983)
 3. Berggren *et al.* (1983)
 4. Salis (1983)

Late Miocene

Datum	Chron	Magnetic polarity Chron and/or Anomaly Correlative	Age (Ma)	Ref.	Remarks
1. LAD <i>Discoaster quinquerramus</i>	5	Event A	5.6	1,2	recorded in lower Gilbert (ref. 7).
2. LAD <i>Discoaster berggrenii</i>	5	Event A	5.6	2	
3. LAD <i>Amaurolithus amplificus</i>	5	Event A	5.6	3	The FAD & LAD of <i>A. amplificus</i> is recorded from a level equivalent to Chron 6 (in a palaeomagnetic gap) & Subchron B respectively in the Mediterranean (ref. 2; = c.6.6 Ma–5.8 Ma).
4. FAD <i>Amaurolithus amplificus</i>	5	Event B	5.9	3	
5. FAD <i>Amaurolithus tricorniculatus</i>	5	Event B	6.0	3	FAD <i>A. tricorniculatus</i> recorded in Subchron A (= c.5.5 Ma) in Mediterranean (ref. 2) & apparently at the same level (along with FAD <i>A. delicatus</i> & <i>A. primus</i>) in Hole 516 F (Rio Grande Rise) at c.5.5 Ma (ref. 4). (See items 6, 7 below.)
6. FAD <i>Amaurolithus primus</i>	6		6.5	2,3	See remarks under item 5, above. Recorded in upper Chron 5 at Site 577 (ref. 7). Recorded just above Thvera Subchron on Fiji (ref. 8).
7. FAD <i>Amaurolithus delicatus</i>	6		6.5	2,3	See remarks under item 5, above.
8. FAD <i>Discoaster quinquerramus</i>	8 (10 of this paper)	mid-anom. 4A	8.2	3,6	
9. LAD <i>Discoaster bollii</i>	8 (10 of this paper)	(lower 4A)	8.3	6	LAD of <i>D. bollii</i> found in interval of no palaeomagnetic data interpreted here as probably equivalent to lower part of anomaly 4A correlative (ref. 6).
10. LAD <i>Catinaster calyculus</i>	8 (10 of this paper)	top normal Subchron just above anom. 5	8.75	6,7	
11. LAD <i>Discoaster exilis</i>	8 (10 of this paper)	base normal Subchron just above anom. 5	8.8	6	
12. LAD <i>Discoaster hamatus</i>	11 (C5)	reversed interval just above anom. 5	8.85	6	
13. LAD <i>Catinaster coalitus</i>	11 (C5)	uppermost anom. 5	9.0	6	
14. FAD <i>Discoaster hamatus</i>	11 (C5)	lower part anom. 5	10.0	6	
15. FAD <i>Catinaster calyculus</i>	11 (C5)	lower part anom. 5	10.0	6	FAD <i>C. calyculus</i> reported subsequent to LAD <i>C. coalitus</i> in Hole 519 (ref. 7); short overlap observed in Hole 563 (ref. 6). FAD of <i>C. calyculus</i> subsequent to that of <i>D. hamatus</i> used to differentiate upper subzone b of Zone CN7. In holes 558 and 563 these two taxa have simultaneous FADs which precludes subdivision of Zone CN7 (see fig. 2).

(lower 4A) = interval of no palaeomagnetic data; identification tentative.

Refs.: 1. Gartner (1973)
2. Mazzei *et al.* (1979)
3. Haq *et al.* (1980)
4. Berggren *et al.* (1983)

5. Ryan *et al.* (1974)
6. Miller *et al.* (in prep.)
7. Poore *et al.* (1983)
8. Rodda *et al.* (in press)

Early Pliocene						
Datum	Chron	Magnetic polarity Chron and/or Anomaly Correlative	Age (Ma)	Ref.	Remarks	
1. FAD <i>Pseudoemiliana lacunosa</i>	G	top Gilbert	3.4	8,11		
2. LAD <i>Sphenolithus abies</i> & <i>S. neoabies</i>	I L B E R T	late Gilbert, between top of chron and Subchron A	3.47	9,11	Found in 2 cores lacking magnetostratigraphy at same level (by correlation; ref. 10). Recorded above Nunivak and above level where Cochiti Subchron expected (but not recorded) on Fiji (ref. 12).	
3. LAD <i>Reticulofenestra pseudoumbilica</i>	(4)	between base Gauss and Gilbert Subchron A	3.5	3,8,9,10	References to younger (c.3.0 Ma) LAD of this taxon may be due to taxonomic problem of younger extension of small, atypical specimens; see discussion in refs 4, 10. Also cited just above Cochiti Subchron (ref. 9). LAD <i>R. pseudo-umbilica</i> recorded in interval above Nunivak and above level where Cochiti Subchron expected (but not recorded) and approximately equivalent to LAD <i>S. abies</i> (see remarks under Datum 2 above) on Fiji (ref. 12).	
4. FAD 'small' <i>Gephyrocapsa</i>	G I L B E R T (4)	upper part of Gilbert	3.6	11	Recorded in DSDP Site 503 and cross correlated to other DSDP holes and to a level near the Zandian–Piacenzian boundary in Italy (ref. 11).	
5. LAD <i>Amaurolithus tricorniculatus</i>		between Mammoth and Cochiti Subchrons	3.7	3–5,8	Associated with C ₁ and C ₂ (Sidufjall and Thvera) Subchrons (undifferentiated) in DSDP Site 297 (off Cape Bojador (c.4.5 Ma) (ref. 6) and between Nunivak and Sidufjall Subchrons (ref. 9) and just above Nunivak Subchron in Fiji (ref. 12).	
6. LAD <i>Amaurolithus delicatus</i>	G I L B E R T	"	3.7	3–6,8,10		
7. FAD <i>Discoaster tamalis</i> .		just above Cochiti Subchron	3.8	6,8	Recorded near Gauss–Gilbert boundary in eastern Pacific Site 503 (ref. 11). Recorded above Nunivak Subchron at a level equivalent to where Cochiti Subchron expected (but not recorded) on Fiji (ref. 12).	
8. FAD <i>Discoaster asymmetricus</i>	(4)	between Cochiti and Nunivak Subchrons	4.1	3–6		
9. LAD <i>Amaurolithus primus</i>		near top of Sidufjall (C ₁)	4.4	6		
10. FAD <i>Ceratolithus rugosus</i>		between C ₁ & C ₂ (Sidufjall Thvera) Subchrons	4.5	3–6,8,10, 11,12	Recorded in mid-Sidufjall (ref. 9). See discussion of redefinition of datum event in ref. 10. Recorded just above Thvera Subchron in Fiji (ref. 12).	
11. LAD <i>Ceratolithus acutus</i> .	G I L B E R T	between C ₁ & C ₂ (Sidufjall & Thvera) Subchrons	4.57	5,6,9	<i>C. rugosus</i> evolved from <i>C. acutus</i> . The respective datum levels of items 9 & 10 are placed at the frequency crossover of these two taxa (ref. 10, 11). Recorded in basal Gilbert in Site 503 (ref. 11). LAD <i>C. acutus</i> recorded just above Thvera Subchron on Fiji (ref. 12).	
12. FAD <i>Ceratolithus acutus</i>		early Gilbert	5.0	3–5,7	associated with gap in paleomagnetic record between Subchrons C ₁ & C ₂ (above) and Chron 5 (below) = early Gilbert = ca. 5.0 Ma at DSDP Site 397 (ref. 6).	
13. LAD <i>Triquetrorhabdulus rugosus</i>	(4)	early Gilbert	5.0	6	see remarks under item 12 above.	

- Refs.: 1. Berggren et al. (1980)
2. Haq et al. (1977)
3. Gartner (1973)
4. Berggren (1973)
5. Berggren et al. (1983)
6. Mazzei, R. et al. (1979)

7. Haq et al. (1980)
8. Poore et al. (1983)
9. Monechi et al. (in press)
10. Backman & Shackleton (1983)
11. Rio (1982)
12. Rodda et al. (in press)

Late Pliocene

Datum	Chron	Magnetic polarity Chron and/or Anomaly Correlative	Age (Ma)	Ref.	Remarks
1. FAD <i>Gephyrocapsa oceanica</i>	M	just above Olduvai Subchron (anom. 2)	1.68	1,2,8	
2. FAD <i>Gephyrocapsa caribbeana</i>	A T U	just below top olduvai Subchron (anom. 2)	1.74	1,2	
3. LAD <i>Discoaster brouweri</i> and <i>D. triradiatus</i>	Y A	just below Olduvai Subchron	1.90	3,6,7,8	Near base or within Olduvai Subchron (ref. 1, 2).
4. FAD <i>Gephyrocapsa aperta</i>	M A	below Olduvai Subchron	2.2	1,2	
5. LAD <i>Discoaster asymmetricus</i>	(2)	below Olduvai Subchron	2.2	7	
6. LAD <i>Discoaster pentaradiatus</i>		reversed interval between Reunion Subchron and top Gauss	2.4	1-8	
7. LAD <i>Discoaster surculus</i>		reversed interval between Reunion Subchron and top Gauss	2.4	1-8	
8. LAD <i>Discoaster tamalis</i>	G A U	latest Gauss	2.6	6,7	Equatorial region only
9. LAD <i>Discoaster decorus</i>	S S (3)	just above Kaena Subchron	2.90	6	First common occurrence recorded near Gauss/Gilbert boundary in Site 503, but sporadically below this level (ref. 8).
10. LAD <i>Discoaster variabilis</i>	GAUSS (3)	just above Kaena Subchron	2.90	7	

- Refs.: 1. Haq *et al.* (1977)
 2. Berggren *et al.* (1980)
 3. Backman *et al.* (1983)
 4. Gartner (1973)
 5. Berggren (1973)
 6. Monechi *et al.* (in press)
 7. Backman and Shackleton (1983)
 8. Rio (1982)

Pleistocene

Datum	Chron	Magnetic polarity Event and/or Anomaly Correlative	Age (Ma)	Ref.	Remarks
1. <i>Gephyrocapsa caribbeana</i> / <i>Emiliana huxleyi</i> dominance-reversal	B R U	1. $\delta^{18}\text{O}$ stage 4	0.073	1,2	Datum event occurs earlier in tropical (low latitude) waters than in transitional (mid-latitude) waters.
2. FAD <i>Emiliana huxleyi</i>	N H E	2. $\delta^{18}\text{O}$ substages 5a-5b	0.275	1,2	
3. LAD <i>Pseudoemiliana lacunosa</i>	S (1)	$\delta^{18}\text{O}$ stage 12	0.474	1,2	
4. LAD <i>Helicosphaera sellii</i>			1.37	5,6	Equatorial region only. Apparently diachronous elsewhere (ref. 5).
5. LAD <i>Calcidiscus macintyreii</i>		between Olduvai and Jaramillo	1.45	3	recorded at top Olduvai Subchron at Site 577 (ref. 4).

- Refs.: 1. Thierstein, J.R. *et al.* (1977)
 2. Berggren, W.A., *et al.* (1980)
 3. Backman *et al.* (1983)
 4. Monechi *et al.* (in press)
 5. Backman and Shackleton (1983)
 6. Rio (1982)

Appendix III

'Tie points' in the comparison of continental biochronology to the Neogene and geomagnetic-polarity time-scale

Equus Datum

Earliest *Equus*, mid MN-16b [2.6] = mid upper Gauss [2.6] Siwaliks; Ponto-Caspian region; France: immigration of *Equus* corresponds to levels with K/Ar ages and MPTS 'dates' in synchrony (4; 6; 11; 20)

Pinjor

Base 'Elephas' zone, early MN-16b [2.8] = upper Gauss [2.8]

Siwaliks, N. Pakistan (Potwar Plateau): mammal faunas with last hipparion, first *Elephas* and cervids, in base of upper normal interval of Gauss (Chron 3) (4; 6; 15)

Arcille (Baccinello V4)

Late Ruscinian, MN-15 [3.7] = late Zanclean, PL2 [3.6] Grosseto, N. Italy: small mammals, with *Miomys* and *Blairinoides*, in lignites lying directly over marine transgressive tongue with *G. margaritae* foram fauna (14).

Anza-Borrego

Early Blancan [4.0] = Gilbert C1 [3.9] Imperial Valley, California: mammals in lower 'Layer Cake' zone of Anza-Borrego sequence are associated with normally magnetized sediments, identified according to a palaeomagnetic profile that extends into the Pleistocene (22).

Yepomera

Latest Hemphillian [4.8] = mid Gilbert C2 [4.6] Chihuahua, Mexico: mammals in normally magnetized sediments overlain by reversely magnetized beds, not yet Blancan but younger than late Hemphillian Mount Eden l.f. (19).

Mount Eden

Latest Hemphillian [5.0] = earliest Gilbert [5.0] San Bernardino, California (San Timoteo badlands): mammals in reversely magnetized beds; palaeomagnetic age constrained by older (Warren) and younger (Yepomera) latest Hemphillian local faunas of south-west N. America found in positively magnetized beds (19).

Tatrot

Base *Hexaprotodon* zone, late MN-15 [5.4] = upper Chron 5 [5.4] Siwaliks, N. Pakistan (Potwar Plateau): mammal faunas with first *Hexaprotodon* in upper normal interval of Chron 5 (6; 15)

Upper Bone Valley

Late Hemphillian [5.5] = Zone N.17-18 [5.2] Southern Florida: mammals in channel-filling deposits associated with end-Miocene rise in sea-level (18; 32).

La Alberca

Latest Turolian, late MN-13 [6.0] = mid N.17 [6.0] Murcia Province, Spain (Fortuna Basin): small mammals, more advanced than late Turolian Crevillente 6, but not yet Ruscinian, in beds intercalated with 'Miocene Terminal' containing *G. conomiozea* — *G. mediterranea* — *G. multiloba* foram fauna (9)

Crevillente 6

Late Turolian, mid MN-13 [6.5] = mid N.17 [6.0]

Alicante Province, Spain (Fortuna Basin): small mammals (with earliest *Apodemus*, *Paraethomys*) similar to Librilla (K/Ar 6.7 Ma), in beds correlated to 'Miocene Terminal' with *G. conomiozea*, *G. mediterranea* foram fauna (9).

Chamita

Late Hemphillian [6.5] = mid Chron 6 [6.2] Rio Grande Valley, New Mexico (Española area): mammals directly equivalent to type Hemphillian (Coffee Ranch, 6.6 Ma) in lengthy reverse-polarity zone; local fission-track ages (c.5.0 Ma) suggesting early Gilbert correlation are discounted (17; 29).

Late Maeotian

Late Turolian, early MN-13 [6.8] = Mollusc zone NSM-6 [7.0] Ukraine region, USSR: mammal faunas (Tudorovo, Avgustovka) with earliest *Protoryx* correlated to mollusc faunas associated with mid Chron 7 (11; 27), in present notation.

Dhok Pathan

Base 'Selenoportax' zone, mid MN-12 [7.5] = lower Chron 7 [7.4] Siwaliks, N. Pakistan (Potwar Plateau): mammal faunas with last *Deinotherium* and first large giraffids, just above Chron 8 (6; 15), in present notation.

Sidi Salem

Early Turolian, MN-11/12 [8.5] = upper N.16 [8.0] N. Algeria, southern Oran district (Beni-Chougrane massif): small mammals at top of Bou Hanifa Formation, unconformably overlain by lower N.17 marine strata (23)

Crevillente 1-3

Earliest Turolian, MN-11 [9.0] = upper N.16 [8.0] Alicante Province, Spain (Fortuna Basin): small mammals, with earliest *Parapodemus*, in beds overlying marine sediments with *G. acostaensis* — *G. pseudomiocenica* foram fauna (9)

North Tejon Hills

Late Clarendonian [9.5] = late early Mohnian, CN7/8 [8.5] S. San Joaquin Valley, California: mammals in shallow marine Chanac Formation, correlative to basal Etchegoin Formation (3; 24; 26; 30).

Nagri

Base 'Hipparion' zone [9.5] = lower Chron C5N1 [10.0] Siwaliks, N. Pakistan (Potwar Plateau): mammal faunas with first Indo-Pakistan area hipparion (F/T 9.5 Ma) located 1/3 up from bottom of 'long normal' (Anomaly 5 correlative) polarity zone (6; 15).

Kastellios

Late Vallesian, early MN-10 [10.5] = earliest N.16 [10.0] Island of Crete: mammals in mid to late Vallesian sites (with primitive hipparions, *Progonomys* spp.) directly overlain by marine strata with *G. acostaensis* — *Neogl. falconarae* — *G. apertura* — *G. ventriosa* foram fauna (8; 10).

South Tejon Hills

Early-mid Clarendonian [10.5] = early Mohnian, CN6/7 [9.8] S. San Joaquin Valley, California: mammals in non-marine upper Santa Margarita Formation, younger than 'Delmontian'

Belridge Diatomite and older than mid-Mohnian Etchegoin Formation (1; 3; 26; 30).

Sycamore Creek

Early Clarendonian [11.5] = early Mohnian, CN6/7 [9.8]
San Francisco Bay, California (Berkeley Hills area): mammals in Cierbo Sandstone Member of San Pablo Formation, correlative to 'Delmontian' upper Monterey Formation in type area (21; 24; 26;).

Khersonian

Late Vallesian, MN-10 [10.5] = Mollusc zone NSM-4 [11.0]
SE Ukraine — Caucasus region, USSR: mammal faunas (Eldar, Berislava) with *Ictitherium*, *Samotherium*, *Miotragocerus*, and 'primigenium'-type hipparion (older than early Maeotian K/Ar 10.0–10.6 Ma), correlated to molluscs associated with lower Chron C5R, in present notation (2; 11;)

Bou Hanifia

Mid-Vallesian, MN-9/10 [11.0] = basal N.16 [10.5]
N. Algeria, Beni-Chougrane massif: mammals (with *Hipparion primigenium*, *Samotherium*, *Progonomys cathalai*, *Zramys*) in beds intertonguing with marine strata containing *G. continuosa* fauna, with tuff (K/Ar 39/40 age of 12.1 Ma) at base; overlies N.14 Anaseur Formation (23)

Comanche point

Early Clarendonian [11.5] = early Mohnian, CN5/6 [10.8]
S. San Joaquin Valley, California (Tejon Hills area): mammals in shallow marine lower Santa Margarita Formation, correlative to 'Delmontian' Belridge Diatomite (1; 21; 26; 30).

Bessarabian

Early Vallesian, MN-9 [12.0] = Mollusc zone NSM-2b [12.5]
Black Sea basin: Mammal faunas (Jeltokamenka) with primitive hipparion and *Anchitherium*, correlated to mollusc faunas associated with upper half of Chron C5A (2; 11), in present notation.

Beglia

Base Vallesian, MN-8/9 [12.5] = Zone N.12 [12.0]
Metlaoui district, central Tunisia (Bled Douarah basin): *Hipparion* datum, in beds that grade northward to late Serravallian lower Saouaf Formation (7; 33)

Volhynian

Latest Astaracian, MN-8 [13.0] = Mollusc zone NSM-1 [13.2]
Azov basin, SE Ukraine: mammal faunas (Kryvoi-Rog) with *Anchitherium*, *Euprox*, and *Aceratherium incisivum* correlated to mollusc faunas associated with Chron C5AB (2; 11), in present notation.

Pojoaque

Late Barstovian [13.5] = Chron C5AA [13.0]
Rio Grande Valley, New Mexico (Española area): mammals in normal-polarity zone in upper Santa Cruz sites, upper Tesuque Formation, correlated to GPTS in dated palaeomagnetic profile (5; 29).

Sharktooth Hill

Mid Barstovian [14.0] = late Luisian, lower CN5a [14.0]
SE San Joaquin Valley, California (Kern River area): mammals, mostly marine, in upper Round Mountain Silt; other mid-Barstovian localities in SW San Joaquin Valley, where the upper Caliente Formation intertongues with

Luisian White Rock Bluff Member of the Branch Canyon Formation (3; 24; 26; 30)

Skull Ridge

Early Barstovian [15.0] = Chron C5AD [14.5]
Rio Grande Valley, New Mexico (Española area): mammals in normal-polarity zone in middle Tesuque Formation, below Santa Cruz sites, correlated to GPTS in dated palaeomagnetic profile (5; 29).

Burkeville

Early Barstovian [15.0] = Zone N8/N9 [15.3]
Texas Gulf Coast: mammals sandwiched between marine transgressive tongues in upper Fleming Formation, 'Potamides matsoni Zone' (13; 30).

Neudorf-Sandberg

Early Astaracian, MN-6 [15.0] = mid CN5a [14.0]
CN5a [14.0]
Devinska Nova Ves, CSSR (lower Morava valley): mammals (including dryopithecines, *Conohyus*, and last *Lis-triodon*) in marine sands of the lower *Bulimina-Bolivina* zone (K/Ar 15.0 Ma) (16; 20; 25; 28; 31;)

Kleinhadersdorf

Early Astaracian, MN-6 [15.5] = basal CN5a [14.5]
CN5a [15.0]
Poysdorf district, N. Austria: mammals (including first dryopithecines, *Conohyus*, *Gazella*) in marine sands of the upper Lagenid zone or basal *Spiroplectamma* zone (16; 25; 28; 31)

Neudorf-spallte

Late Orleanian, MN-5 [16.0] = early Badenian, mid CN4 [15.5]
Devinska Nova Ves, CSSR (lower Morava valley): mammals in fissure deposits (with pliopithecines, *Dicroceros*, *Palaeomeryx*, *Taucanomo*) overlain by transgressive marine beds of lower Lagenid zone (K/Ar 16.5 Ma) (12; 16; 20; 25; 31)

Barker's Ranch

Latest Hemingfordian [17.0] = early Relizian, CN3 [17.5]
S. San Joaquin Valley, California (Kern River area): marine and terrestrial mammals in Olcese Sand, intertonguing with base of Round Mountain Silt. In SW San Joaquin Valley, other late Hemingfordian localities occur in the upper Caliente Formation, which intertongues with the lower Relizian Saltos Shale Member of the Branch Canyon Formation (3; 21; 24; 26; 30).

Midway

Late Hemingfordian [17.5] = Zone N6–N7 [17.6]
Florida panhandle: mammals in upper Torreya Formation, which intertongues with basal Chipola Formation (13; 18; 30).

Seaboard

Mid Hemingfordian [18.5] = mid N.6 [18.5]
Florida panhandle: mammals in middle Torreya Formation: also in central Florida, where mid-Hemingfordian Thomas Farm mammals occur at the same level in lower Hawthorne Formation (13; 18; 30).

Cuyama Pato Red

Latest Arikarean [21.0] = Mid Saucian, CN1c [20.5]
Transverse Ranges, California (Cuyama Valley area): mammal localities in Pato Red Sandstone, which intertongues

with 'Upper Vaqueros' Painted Rock Sandstone. (3; 26).

Pyramid Hill

Late Arikareean [22.0] = early Saucesian, CN1b/1c [22.5]
S. San Joaquin Valley, California (Kern River area):
mammals (with *Anchitherium*) at base of Jewett Sand; just
above Tecuja Dacite (K/Ar 22.3 Ma). In SW San Joaquin
Valley, other late Arikareean mammal localities occur in the
Lower Caliente Formation, which intertongues with earliest
Saucesian Agua Sandstone of Santos Shale Formation (3; 21;
26).

References: ¹Addicott 1972; ²Andreescu 1979; ³Armentrout
& Echols 1981; ⁴Azzaroli & Napoleone 1981; ⁵Barghoorn

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⁸Bruijn *et al.* 1971; ⁹Bruijn, *et al.* 1975; ¹⁰Bruin & Zachariasse
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Opdyke *et al.* 1982; ¹⁶Lehotayova & Molcikova 1978;
¹⁷MacFadden 1977; ¹⁸MacFadden & Webb 1982; ¹⁹May &
Repenning 1982; ²⁰Mein 1979; ²¹Obradovich & Naeser 1981;
²²Opdyke, *et al.* 1977; ²³Ouda & Aneur 1979; ²⁴Poore *et al.*
1982; ²⁵Rabeder 1978; ²⁶Savage & Barnes 1972; ²⁷Semenenko
& Pevzner 1979; ²⁸Steininger 1977; ²⁹Tedford 1981; ³⁰Tedford
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