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One hundred million years of geomagnetic polarity history

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ABSTRACT

Since 1968, absolute ages have been assigned to the Late Cretaceous–Cenozoic geomagnetic reversal time scale by fixing the ages of two or more calibration points in a composite marine magnetic-anomaly profile and interpolating between or extrapolating beyond these points, assuming constant spreading rates in each interval. Previously, no more than 4 calibration points were used, but it is now possible to specify 11 calibration points, in addition to the 0 m.y. datum. This improvement is based on magnetostratigraphic studies in Italian pelagic limestones; these studies closely tie the geomagnetic reversal sequence to the foraminiferal and coccolith zonations. Absolute ages of calibration points are provided by the best available dates on stage boundaries, which are located from the biostratigraphic zonation. The greatest changes from previous scales come in the late Paleocene–early Eocene, where the new ages are as much as 3 m.y. younger than in the 1977 scale of LaBrecque and others, and as much as 1.8 m.y. younger than in the 1980 scale of Ness and others.

INTRODUCTION

A major goal of geochronology is to tie together the three principal time scales, which are based on evolutionary changes recorded by fossils, on "absolute age" determined from radioactive decay, and on the sequence of geomagnetic reversals recorded by spreading oceanic crust and in stratigraphic sequences. The compendium of papers edited by Cohee and others (1978), dealing largely with absolute-age calibration of the paleontological time scale, is still up to date. Absolute ages have been applied to the reversal sequence principally by fixing the ages of two or more calibration points in a composite marine magnetic-anomaly profile and interpolating between or extrapolating beyond these points, assuming constant spreading rates in each interval. Ness and others (1980) gave a valuable review of the successive versions of this type of time scale for the Late Cretaceous and Cenozoic and offered a revised version as an "up-to-date but temporary synthesis."

At this point it is possible to make a further substantial revision of the Late Cretaceous–Cenozoic magnetic-polarity time scale on the basis of new magnetostratigraphic information from pelagic limestones in Italy. This revision provides a very close tie between the reversal sequence and the planktic foraminiferal biozonation. The widely used time scale of LaBrecque and others (1977) was based on two calibration points, and that of Ness and others (1980) employed four, but it is now possible to fix the biozonal positions, and thus indirectly the absolute ages, of 11 calibration points in the reversal sequence. (The present is an additional calibration point in all cases.)

Magnetostratigraphic studies in Italy have yielded a reversal sequence with a fingerprint of long and short polarity zones which almost exactly matches the marine magnetic-anomaly sequence of LaBrecque and others (1977) and which has been paleontologically dated on the basis of abundant foraminifera, with coccoliths employed in certain intervals. This paleontological information fixes the positions in the reversal sequence of chronologic boundaries to the stage level in the Late Cretaceous and the Tertiary. Using the currently accepted absolute ages for these boundaries, we are able to fix the ages of 9 calibration points in the magnetic polarity sequence from the base of the Campanian to the Oligocene-Miocene boundary; for Miocene and younger we use the previously established calibration points of Ness and others (1980). The polarity sequence of LaBrecque and others (1977) has been adjusted to these dates using linear interpolation between calibration points.

MAGNETOSTRATIGRAPHY

The pelagic limestones and marls of the Umbrian sequence in northern peninsular Italy have yielded excellent records of magnetic polarity and foraminiferal evolution. These records can be precisely linked because for each stratigraphic level the magnetic and paleontological information both come from the same small sample.

Figure 1 shows the Umbrian and southern Alpine sections for which detailed magnetic stratigraphy has been measured. The Cretaceous results have been reviewed by Lowrie and others (1980b). Details have been presented in the following papers: Contessa Quarry, Road, and Highway: Lowrie and others (1981); Bottaccione: Premoli Silva and others (1974), Lowrie and Alvarez (1975, 1977a, 1977b), Roggenthen and Napoleone (1977), Alvarez and others (1977), G. Napoleone and others (in prep.); Moria: Alvarez and Lowrie (1978), Vandenberg and others (1978); Furlo Upper Road: W. Alvarez and W. Lowrie (in prep.); Poggio le Guaine, Gorgo a Cerbara: Lowrie and others (1980a); Valdorbia: Vandenberg and others (1978), Lowrie and others (1980a); Cismon, in the southern Alps: Channell and others (1979). The Umbrian magnetic stratigraphy has been confirmed by work on Deep Sea Drilling Project (DSDP) Legs 73 (Tauxe and others, 1980) and 74 (Chave, 1980).

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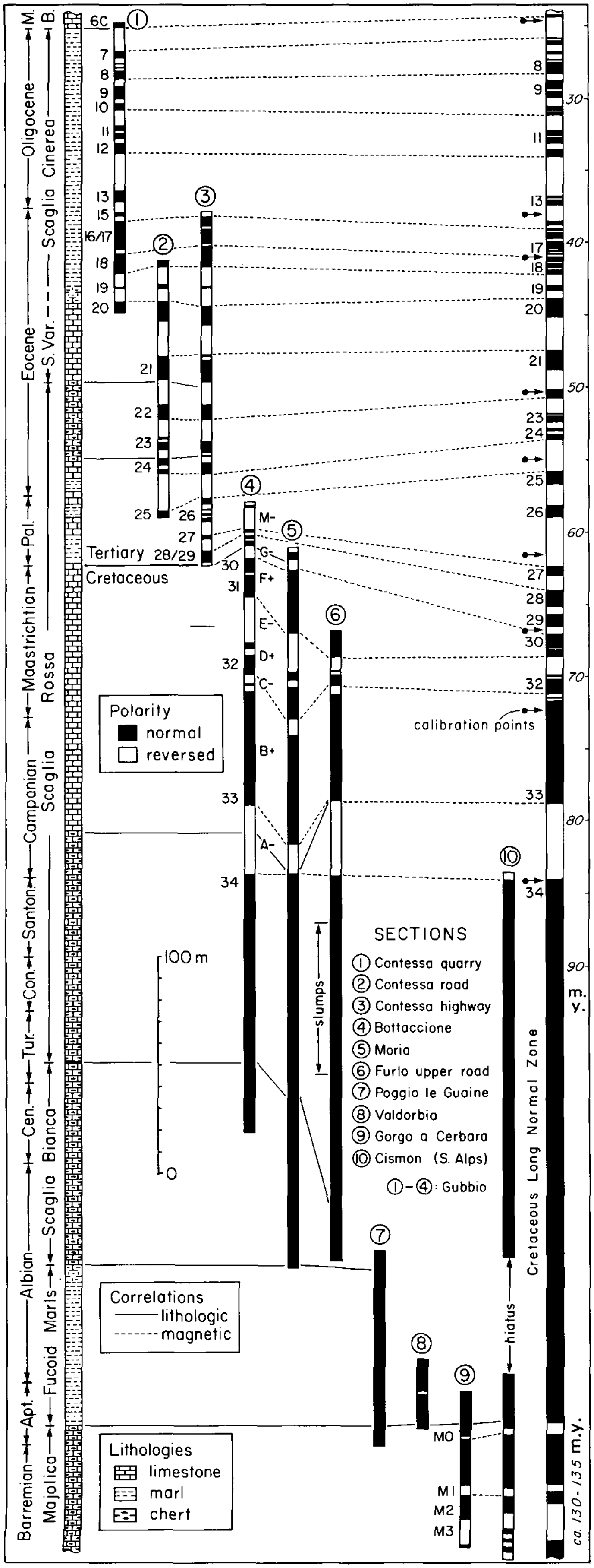


Figure 1. Correlation of magnetostratigraphic sections in Umbrian Apennines and southern Alps with sea-floor magnetic anomalies. Left-hand columns: age (from foraminiferal zonation), formation names, and lithology (M. = Miocene, S.Var. = Scaglia Variegata, B. = Bisciaro). Columns 1-10: detailed magnetostratigraphic sections (references given in text). Column 4 has been extended upward to anomaly 18 in recent work by G. Napoleone and others (in prep.). Numbers are standard magnetic-anomaly identification; letters in column 4 give Gubbio magnetic zonation (Alvarez and others, 1977). Right-hand column: magnetic-reversal sequence determined from sea-floor magnetic anomalies by LaBrecque and others (1977) and redated in this paper by interpolation between the nine paleontologically controlled calibration points marked by arrows. Absolute ages of M-sequence reversals are uncertain.

BIOSTRATIGRAPHY

The Umbrian sections have been zoned with planktic foraminifera by Premoli Silva (1977; and *in* Lowrie and others, 1980a, and *in* G. Napoleone and others, in prep.); Premoli Silva and others (1976), and Premoli Silva and Toumarkine (*in* Lowrie and others, 1981). Nannoplankton zonations have been made by Monechi (1979; and *in* Lowrie and others, 1980a) and by Perch-Nielsen (*in* Lowrie and others, 1981). The southern Alps section was zoned on the basis of foraminifera and nannoplankton by Medizza (*in* Channell and others, 1979).

The result of these magnetostratigraphic and biostratigraphic studies has been to fix the positions in the magnetic-polarity sequence where various appearances and extinctions of planktic foraminifera and coccolith taxa occur. The most significant relocation concerns the Paleocene-Eocene boundary. This was located by Heirtzler and others (1968) within anomaly 21 by extrapolation from present spreading rates in the South Atlantic. It was relocated within anomaly 23 by interpolation in the time scale of LaBrecque and others (1977), and readjustment of the age of the boundary placed it at the base of anomaly 24 (Ness and others, 1980). None of these locations was done directly. However, recent magnetostratigraphic results from Italian pelagic limestones (Lowrie and others, 1981) and in vertebrate-bearing continental sediments (Butler and others, 1981) locate the Paleocene-Eocene boundary within the negative polarity zone just younger than anomaly 25. As a result of this shift of the boundary location toward higher anomaly numbers and revision of the date of the boundary, sea-floor spreading rates and the timing of major events related to sea-floor spreading changes in early Tertiary time have been altered substantially (Coney and Butler, 1980; Butler and Coney, 1981).

ABSOLUTE-AGE CALIBRATION

After discussions with colleagues actively working on biostratigraphic and radiometric questions, we have decided to follow Ness and others (1980) in accepting the ages given for the late Tertiary by Berggren and Van Couvering (1974), for the early Tertiary by Hardenbol and Berggren (1978), and for the Late Cretaceous by Obradovich and Cobban (1975). These ages have been corrected by Ness and others (1980) for the new decay and abundance constants used in K-Ar dating, so our time scale from the base of the Cenomanian to the present is identical to the right-hand column of their Table 1. For the Early Cretaceous, where absolute age calibration is much more uncertain, we use the time scale of Lanphere and Jones (1978), but unfortunately the Barremian, the most critical stage for our purposes, cannot yet be dated with any certainty. The chronologies we have chosen differ from some other available systems, notably those of Van Hinte (1976) and Odin (1978). A discussion of the relative merits of the various proposed chronologies would be out of place here; we justify our choices on the basis of arguments presented by

Berggren and others (1978), Lanphere and Jones (1978), and Ness and others (1980). The set of boundary ages used in this paper is given in Table 1.

CONSTRUCTION OF THE NEW TIME SCALE

The polarity sequence in the magnetic time scale of LaBrecque and others (1977) assumes a constant rate of sea-floor spreading in the South Atlantic during the Tertiary and in the North Pacific during the Maastrichtian and Campanian. The stage and substage boundaries used as calibration levels (Table 1) were located in the polarity sequence of LaBrecque and others (1977) on the basis of the Italian magnetostratigraphic studies, and their ages were specified as in Ness and others (1980, Table 1). The revised ages of polarity-zone boundaries were then obtained by linear interpolation between calibration points, using the reversal spacings from LaBrecque and others (1977). Our revised time scale is thus related to previous time scales as follows:

(1) for $O \le t_R \le 10.30$, $(O \le t_N \le 10.30)$, $(O \le t_L \le 9.74)$, $t_R = t_N$;

(2) for $10.30 \le t_R \le 84.02$, $(10.30 \le t_N \le 85.86)$, $(9.74 \le t_L \le 79.65)$, $t_R = t_R(Y) + [t_R(O) - t_R(Y)]\,[t_L - t_L(Y)]/[t_L(O) - t_L(Y)]$,

where t_L, t_N, and t_R are ages (m.y.) in the LaBrecque and others (1977), Ness and others (1980), and present revised time scales, respectively. Note that upper-case O and Y refer to the older and younger calibration points that bound the interval of interest, whereas lower-case o and y used in Table 1 and in Ness and others (1980) refer to the older and younger limits of polarity intervals. Table 2 gives the revised ages for all polarity-zone boundaries.

The apparent precision of 0.01 m.y. in the revised time scale (Table 2) is not the absolute accuracy of the scale but is necessary to portray correctly the relative durations of short polarity intervals. LaBrecque and others (1977) included polarity intervals shorter than 40,000 yr in their Table 1, but they omitted these from their figures. "Tiny wiggles" on anomaly profiles can be due to short duration reversals or to geomagnetic intensity fluctuations (see LaBrecque and others, 1977, for a discussion of the problem). Because of this ambiguity, we have omitted all polarity intervals shorter than 40,000 yr from our Table 2 and from the graphical representations of the new magnetic time scale for the Cenozoic (Fig. 2) and Late Cretaceous (Fig. 3). For completeness, the scale has been extended down into the Cretaceous for those stages whose boundaries are reasonably well dated. The Late Cretaceous stage-boundary ages shown are those recomputed by Ness and others (1980) from the radiometric dates of Obradovich and Cobban (1975).

We have restricted our revision of the magnetic time scale to the Cenozoic and Late Cretaceous. At present there are not enough reliable radiometric dates for the Early Cretaceous and Late Jurassic stage boundaries to justify presenting a new magnetic time scale for these times. A tentative comparison of geomagnetic polarity sequences in the Cretaceous as derived from magnetostratigraphic sections and oceanic magnetic anomalies was made by Lowrie and others (1980b). This used the proposed numeric time scale of Van Hinte (1976), which, like other time scales preceding it, was largely intuitive for the Early Cretaceous stages. However, magnetostratigraphic studies in Italian pelagic limestones have firmly correlated the long normal-polarity zone prior to the Campanian (Fig. 3) with the Cretaceous magnetic smooth zone in the oceanic magnetic anomalies (Lowrie and Alvarez, 1977a, 1977b; Alvarez and others, 1977) Channell and others, 1979). The youngest of the M-sequence anomalies pre-

TABLE 1. CALIBRATION LEVELS FOR THE NEW MAGNETIC TIME SCALE

Calibration level	Location in anomaly sequence*	Previous† age (m.y.)	Revised age (m.y.)
Present	--	0.00	0.0
Pliocene (reversal boundary)	2.3'(o)	3.32	3.4§
Early late Miocene (reversal boundary)	5.5(o)	9.74	10.3§
Miocene/Oligocene boundary	Below 6C	24.2	24.6
Oligocene/Eocene boundary	13-15	36.4	38.0
Late/middle Eocene	Below 18(y)	41.5	41.0
Middle/early Eocene	Below 22(y)	52.5	50.3
Eocene/Paleocene boundary	24-25	58.2	54.9
Late/early Paleocene#	26-27	61.8	61.5
Tertiary/Cretaceous boundary	29-30	65.0	66.7
Maastrichtian/Campanian boundary	33	72.5	72.3
Campanian/Santonian boundary	33-34(o)	79.7	84.1

* Anomalies are numbered as in Ness and others (1980); (o) and (y) refer to the reversals at the older and younger ends of a polarity interval.

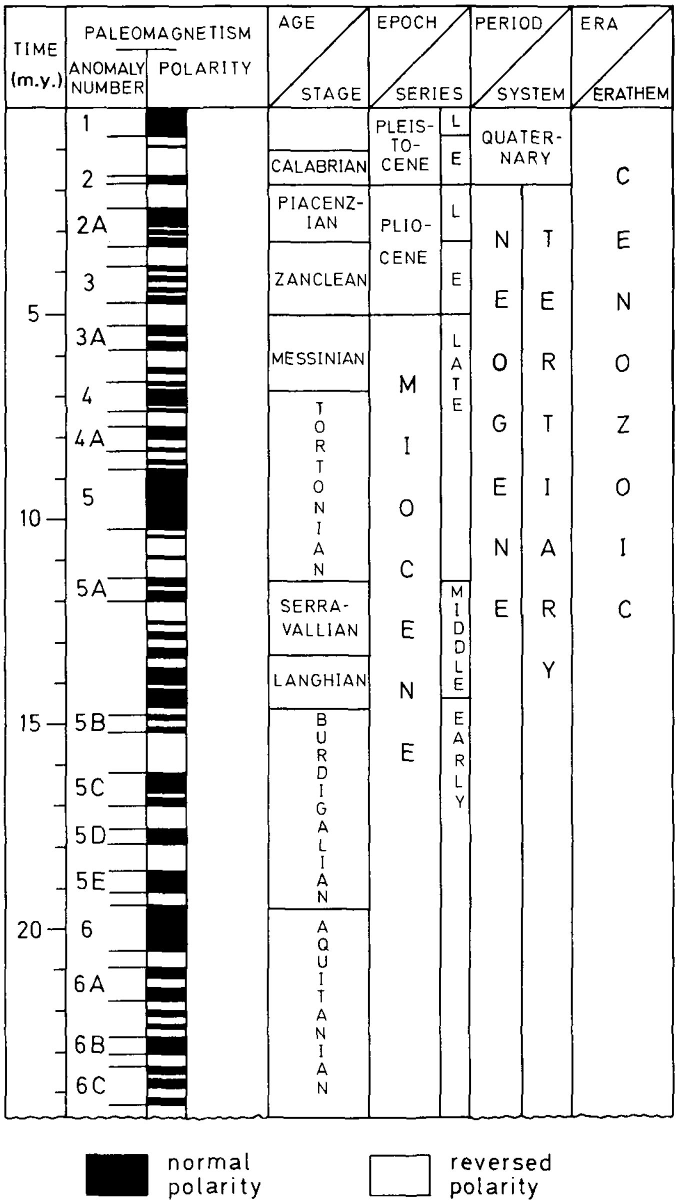
† In the LaBrecque and others (1977) time scale.

§ Revised ages from Ness and others (1980).

\# Taken as the angulata/uncinata boundary (Hardenbol and Berggren, 1978).

TABLE 2. DURATIONS OF NORMAL POLARITY INTERVALS

Time interval (m.y.)	Anomaly	Time interval (m.y.)	Anomaly
0.00 - 0.72	1	25.74 - 25.86	7
0.91 - 0.97		25.94 - 26.27	7
1.66 - 1.87	2	26.73 - 26.94	7A
2.47 - 2.91	2A	27.27 - 27.36	8
2.98 - 3.07	2A	27.44 - 28.27	8
3.17 - 3.40	2A	28.73 - 29.39	9
3.87 - 3.97	3	29.45 - 29.92	9
4.10 - 4.24	3	30.50 - 30.84	10
4.39 - 4.46	3	30.90 - 31.18	10
4.56 - 4.76	3	32.19 - 32.59	11
5.33 - 5.52	3A	32.65 - 33.12	11
5.67 - 5.87	3A	33.57 - 34.07	12
6.34 - 6.47		36.75 - 36.96	13
6.68 - 6.75	4	37.03 - 37.41	13
6.83 - 7.25	4	38.51 - 38.77	15
7.32 - 7.38	4	39.02 - 39.16	16
7.77 - 8.09	4A	39.26 - 39.43	16
8.29 - 8.38	4A	39.47 - 39.71	16
8.59 - 8.68		39.88 - 40.42	17
8.80 - 10.30	5	40.46 - 40.59	17
10.42 - 10.47		40.63 - 40.84	17
10.91 - 10.98		40.94 - 41.30	18
11.46 - 11.64	5A	41.36 - 41.74	18
11.76 - 12.03	5A	41.79 - 42.17	18
12.50 - 12.54		42.92 - 43.32	19
12.76 - 12.94		43.83 - 45.14	20
13.14 - 13.40		47.37 - 48.75	21
13.63 - 14.04		50.14 - 50.70	22
14.16 - 14.62		51.74 - 51.87	23
14.83 - 14.93	5B	51.91 - 52.42	23
15.10 - 15.23	5B	52.79 - 52.97	24
16.21 - 16.73	5C	53.21 - 53.61	24
16.80 - 16.99	5C	55.76 - 56.66	25
17.59 - 17.92	5D	58.15 - 58.95	26
18.60 - 19.13	5E	62.31 - 63.00	27
19.41 - 20.52	6	64.00 - 65.12	28
20.96 - 21.24	6A	65.63 - 66.54	29
21.47 - 21.79	6A	66.98 - 68.01	30
21.99 - 22.15		68.07 - 68.62	31
22.35 - 22.44		69.84 - 70.01	32
22.66 - 23.07	6B	70.17 - 71.18	32
23.37 - 23.54	6C	71.43 - 71.46	
23.66 - 23.90	6C	71.64 - 78.82	33
24.15 - 24.32	6C	84.02 -	34



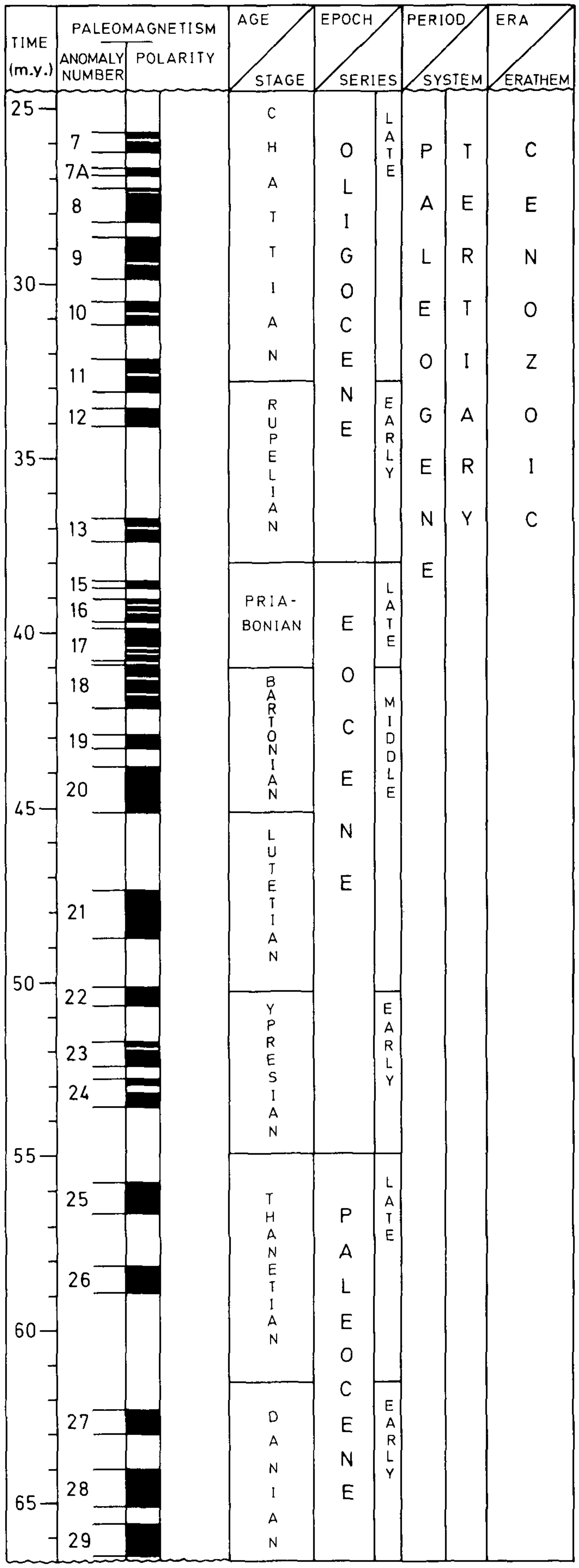


Figure 2. Revised magnetic-polarity time scale for Cenozoic, prepared by locating Paleocene, Eocene, and Oligocene stage and substage boundaries in oceanic magnetic-anomaly reversal sequence by magnetostratigraphic correlations (Fig. 1). Revised radiometric ages (Ness and others, 1980) were then associated with 9 Cenozoic calibration points (Table 1), and intervening anomalies were dated by interpolation.

ceding this quiet zone have been tied into the Early Cretaceous biostratigraphic framework in Italian sections; anomaly M0 occurs at the base of the Aptian and anomaly M1 in the middle of the Barremian. These dates are about half a stage older than the corresponding ages estimated by Larson and Hilde (1975).

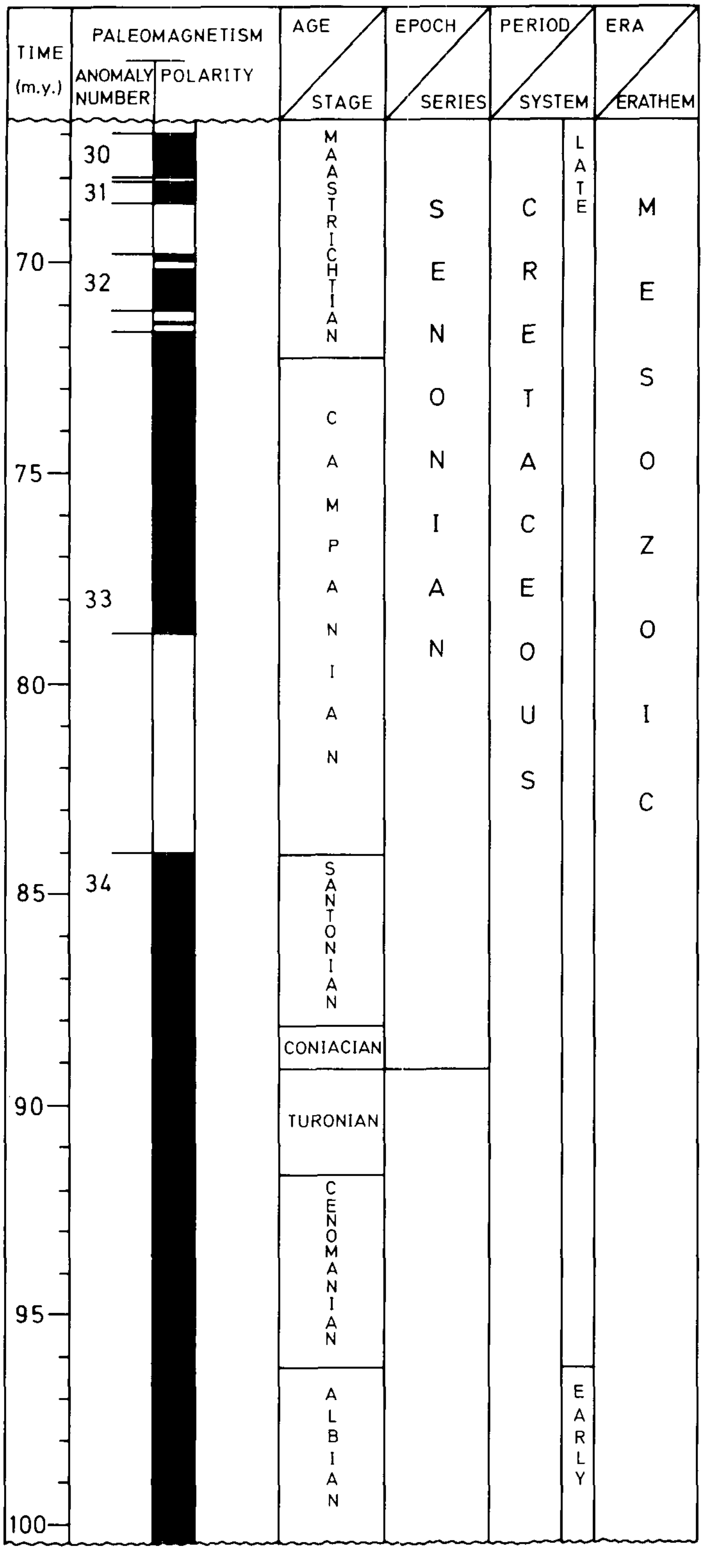


Figure 3. Revised magnetic-polarity time scale for Late Cretaceous, prepared similarly to Figure 2. Maastrichtian and Campanian reversal sequences have been interpolated between appropriate calibration points (Table 1). Ages of Albian to Santonian stage boundaries in Cretaceous quiet interval correspond to dates of Obradovich and Cobban (1975), as revised by Ness and others (1980).

Unfortunately, there are no reliable dates for the boundaries of these critical stages. Lanphere and Jones (1978) cited two dates closely straddling the Hauterivian-Barremian boundary at 136 m.y. and two further dates at 114 and 120 m.y. for levels within the Albian.

COMPARISON TO DSDP DATING

LaBrecque and others (1977) tested their time scale by plotting, in their Figure 4, the paleontologically determined age of the sediment found immediately above basement in various DSDP holes against the age of the crust predicted on the basis of the magnetic anomaly at the drill site, with the anomalies dated according to their proposed time scale. The observed ages agreed fairly well with the predicted ages, with divergences, as they noted, in the late Paleocene–early Eocene and in the middle Miocene. In Figure 4 here, we give a similar plot, adding three recent DSDP sites (408, 410, 442), and using our new dating of the anomalies. Comparison of this figure with Figure 4 of LaBrecque and others (1977) shows the improvement resulting from revision of the time scale. The Paleocene-Eocene discrepancy has been eliminated. The remaining problems are with Miocene sites 15, 36, and 396, in the only part of the anomaly sequence that has not yet been calibrated by magnetostratigraphic studies.

As LaBrecque and others (1977) stressed, a plot of this kind does not test the validity of the absolute ages assigned to the magnetic anomalies, because these age assignments are based on acceptance of one particular set of dates for the paleontological stage boundaries. What Figure 4 demonstrates is that DSDP information agrees with the correlation between foraminiferal biostratigraphy and polarity zones determined in Italian limestones. This was previously demonstrated for the Late Cretaceous and Paleocene by Larson (1976).

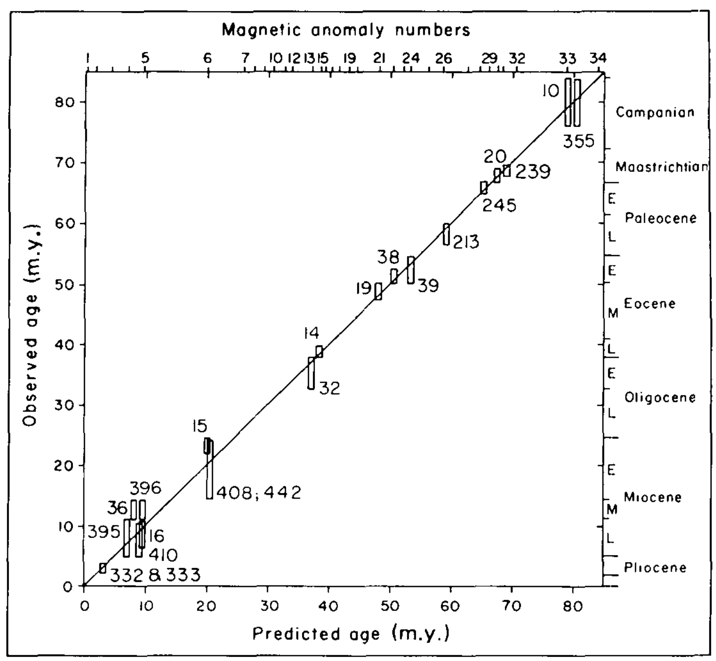


Figure 4. Comparison of paleontological ages of basal sediments in DSDP holes with basement ages predicted from magnetic anomalies. Sites intersected by 45° line show agreement between predicted and observed age. Comparison of this plot with Figure 4 of LaBrecque and others (1977) shows that discrepancies in Paleocene-Eocene have been removed. As discussed in text, this plot tests correlation of magnetic-reversal sequence to foraminiferal biostratigraphy, *not* absolute ages assigned to polarity zones.

REFERENCES CITED

Alvarez, W., and Lowrie, W., 1978, Upper Cretaceous paleomagnetic stratigraphy at Moria (Umbrian Apennines, Italy): Verification of the Gubbio section: Royal Astronomical Society Geophysical Journal, v. 55, p. 1-17.

Alvarez, W., Arthur, M. A., Fischer, A. G., Lowrie, W., Napoleone, G., Premoli Silva, I., and Roggenthen, W. M., 1977, Upper Cretaceous-Paleocene magnetic stratigraphy at Gubbio, Italy—V. Type section for the Late Cretaceous-Paleocene geomagnetic reversal time scale: Geological Society of America Bulletin, v. 88, p. 383-389.

Berggren, W. A., and Van Couvering, J. A., 1974, Biostratigraphy, geochronology and paleoclimatology of the last fifteen million years in marine and continental sequences: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 16, p. 1-216.

Berggren, W. A., McKenna, M. C., Hardenbol, J., and Obradovich, J. D., 1978, Revised Paleogene polarity time scale: Journal of Geology, v. 86, p. 67-81.

Butler, R. F., and Coney, P. J., 1981, A revised magnetic polarity time scale for the Paleocene and early Eocene and implications for Pacific plate motion: Geophysical Research Letters (in press).

Butler, R. F., Gingerich, P. D., and Lindsay, E. H., 1981, Magnetic polarity stratigraphy and biostratigraphy of Paleocene and Lower Eocene continental deposits, Clark's Fork Basin, Wyoming: Journal of Geology (in press).

Channell, J.E.T., Lowrie, W., and Medizza, F., 1979, Middle and Early Cretaceous magnetic stratigraphy from the Cismon section, northern Italy: Earth and Planetary Science Letters, v. 42, p. 153-166.

Chave, A. D., 1980, Upper Cretaceous-Paleocene magnetic stratigraphy, DSDP Leg 74 [abs.]: EOS (American Geophysical Union Transactions), v. 61, p. 944.

Cohee, G. V., Glaessner, M. F., and Hedberg, H. D., eds., 1978, Contributions to the geologic time scale: American Association of Petroleum Geologists Studies in Geology, v. 6, 338 p.

Coney, P. J., and Butler, R. F., 1980, Coincidence of Hawaiian-Emperor bend with changes in Pacific-Farallon spreading [abs.]: EOS (American Geophysical Union Transactions), v. 61, p. 947.

Hardenbol, J., and Berggren, W. A., 1978, A new Paleogene numerical time scale: American Association of Petroleum Geologists Studies in Geology, v. 6, p. 213-234.

Heirtzler, J. R., Dickson, G. O., Herron, E. M., Pitman, W. C., III, and LePichon, X., 1968, Marine magnetic anomalies, geomagnetic field reversals, and motions of the ocean floor and continents: Journal of Geophysical Research, v. 73, p. 2119-2136.

LaBrecque, J. L., Kent, D. V., and Cande, S. C., 1977, Revised magnetic polarity time scale for Late Cretaceous and Cenozoic time: Geology, v. 5, p. 330-335.

Lanphere, M. A., and Jones, D. L., 1978, Cretaceous time scale from North America, *in* Cohee, G. V., Glaessner, M. F., and Hedberg, H. D., eds., Contributions to the geologic time scale: American Association of Petroleum Geologists Studies in Geology, v. 6, p. 259-268.

Larson, R. L., 1976, Deep sea drilling results related to the paleomagnetic and paleontologic stratigraphy at Gubbio: Società Geologica Italiana Memorie, v. 15, p. 61-67.

Larson, R. L., and Hilde, T.W.C., 1975, A revised time scale of magnetic reversals for the Early Cretaceous and Late Jurassic: Journal of Geophysical Research, v. 80, p. 2586-2594.

Lowrie, W., and Alvarez, W., 1975, Paleomagnetic evidence for rotation of the Italian Peninsula: Journal of Geophysical Research, v. 80, p. 1579-1592.

——1977a, Upper Cretaceous-Paleocene magnetic stratigraphy at Gubbio, Italy—III. Upper Cretaceous magnetic stratigraphy: Geological Society of America Bulletin, v. 88, p. 374-377.

——1977b, Late Cretaceous geomagnetic polarity sequence: Detailed rock and paleomagnetic studies of the Scaglia Rossa limestone at Gubbio, Italy: Royal Astronomical Society Geophysical Journal, v. 51, p. 561-581.

Lowrie, W., Alvarez, W., Premoli Silva, I., and Monechi, S., 1980a, Lower Cretaceous magnetic stratigraphy in Umbrian pelagic carbonate rocks: Royal Astronomical Society Geophysical Journal, v. 60, p. 263-281.

Lowrie, W., Channell, J.E.T., and Alvarez, W., 1980b, A review of magnetic stratigraphy investigations in Cretaceous pelagic carbonate rocks: Journal of Geophysical Research, v. 85 (Norman Watkins memorial issue), p. 3597-3605.

Lowrie, W., Alvarez, W., Napoleone, G., Perch-Nielsen, K., Premoli Silva, I., and Tourmarkine, M., 1981, Eocene and Oligocene magnetic stratigraphy in Umbrian pelagic carbonate rocks: Geological Society of America Bulletin (in press).

Monechi, S., 1979, Variations in nannofossil assemblage at the Cretaceous/Tertiary boundary in the Bottaccione section (Gubbio, Italy): University of Copenhagen, Cretaceous-Tertiary Boundary Events Symposium, v. 2, p. 164-169.

Ness, G., Levi, S., and Couch, R., 1980, Marine magnetic anomaly timescales for the Cenozoic and Late Cretaceous: A précis, critique and synthesis: Reviews of Geophysics and Space Physics, v. 18, p. 753-770

Obradovich, J. D., and Cobban, W. A., 1975, A time-scale for the Late Cretaceous of the western interior of North America: Geological Association of Canada Special Paper 13, p. 31-54.

Odin, G. S., 1978, Isotopic dates for a Paleogene time scale, *in* Cohee, G. V., Glaessner, M. F., and Hedberg, H. D., eds., Contributions to the geologic time scale: American Association of Petroleum Geologists Studies in Geology, v. 6, p. 247-257.

Premoli Silva, I., 1977, Upper Cretaceous-Paleocene magnetic stratigraphy at Gubbio, Italy—II. Biostratigraphy: Geological Society of America Bulletin, v. 88, p. 367-389.

Premoli Silva, I., Napoleone, G.,and Fischer, A. G., 1974, Risultati preliminari sulla stratigrafia paleomagnetica della Scaglia cretaceopaleocenica della sezione di Gubbio (Appennino centrale): Società Geologica Italiana Bollettino, v. 93, p. 647-659.

Premoli Silva, I., Paggi, L., and Monechi, S., 1976, Cretaceous through Paleocene biostratigraphy of the pelagic sequence at Gubbio, Italy: Società Geologica Italiana Memorie, v. 15, p. 21-32.

Roggenthen, W. M., and Napoleone, G., 1977, Upper Cretaceous-Paleocene magnetic stratigraphy at Gubbio, Italy—IV. Upper Maastrichtian-Paleocene magnetic stratigraphy: Geological Society of America Bulletin, v. 88, p. 378-382.

Tauxe, L., LaBrecque, J. L., Hsü, K., and others, 1980, Paleogene magnetostratigraphy from DSDP Leg 73: Geological Society of America Abstracts with Programs, v. 12, p. 533.

Vandenberg, J., Klootwijk, C. T., and Wonders, A.A.H., 1978, Late Mesozoic and Cenozoic movements of the Italian Peninsula: Further paleomagnetic data from the Umbrian sequence: Geological Society of America Bulletin, v. 89, p. 133-150.

Van Hinte, J. E., 1976, A Cretaceous time scale: American Association of Petroleum Geologists Bulletin, v. 60, p. 498-516.

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