Towards a Quaternary Time Scale[1]

W. A. BERGGREN

Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543

L. H. BURCKLE

Lamont – Doherty Geological Observatory, Palisades, New York 10964

M. B. CITA

Institute of Geology and Paleontology, University of Milan, Piazzale Gorini 15, Milan, Italy

H. B. S. COOKE

Department of Geology, Dalhousie University, Halifax, Nova Scotia, Canada

B. M. FUNNELL

School of Environmental Science, University of East Anglia, University Plain, Norwich NR4 7TJ, England

S. GARTNER

College of Geosciences, Department of Oceanography, College Station, Texas 77843

J. D. HAYS

Lamont – Doherty Geological Observatory, Palisades, New York 10964

J. P. KENNETT

Graduate School of Oceanography University of Rhode Island Kingston, Rhode Island 02881

N. D. OPDYKE

Lamont – Doherty Geological Observatory, Palisades, New York 10964

L. PASTOURET

CNEXO Centre Oceanologique de Bretagne, 29 N. Plouzane, B.P. 337, Brest, France

N. J. SHACKLETON

Godwin Laboratory for Quaternary Research, Free School Lane, Cambridge CB2 3RS, England

Y. TAKAYANAGI

Institute of Paleontology, Tohoku University, Sendai, Japan

Nine first-appearance datums (FADs), twenty-three last-appearance datums (LADs), and three other micropaleontological datums are related to the magnetic-reversal, oxygen-isotope, and calcite-dissolution/coarse-fraction time scales to provide a preliminary basis for subdivision of the Quaternary in deep-sea sediments. The magnetic-reversal, oxygen-isotope, and calcite-dissolution/coarse-fraction scales have been correlated by determination on the same core materials, and absolute dates applied by $^{40}K/^{40}Ar$ or ^{14}C dating of materials in known positions on one or another of these scales. FADS and LADs have been determined in cores for which either a magnetic-reversal, oxygen-isotope, or calcite-dissolution/coarse-fraction scale has also been available. Altogether 3 FADs and 5 LADs based on diatoms, 4 FADs and 5 LADs based on calcareous nannoplankton, 1 FAD and 8 LADs based on radiolarians, 1 FAD and 5 LADs based on planktonic foraminifers, 2 acme datums, and 1 ratio reversal datum have been determined, and absolute dates inferred by interpolation from known dates on the reference time scales. Some of the FADs and LADs apply or are synchronous only over limited areas of the oceans; others appear to be synchronous throughout the oceans. The base of the Quaternary is set at the top of the Olduvai event at 1.7 my. Four FADs, twelve LADs, two acme datums, and one ratio reversal datum occur above the base of the Quaternary at an average rate of about 1 per 100,000 yr. Five FADs and twelve LADs are recognized in the 0.8-my interval between the top of the Olduvai event and the Gauss/Matuyama boundary at 2.5 my at an average incidence of about 1 per 50,000 yr.

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[1] Compiled by W. A. Berggren (Woods Hole Oceanographic Institution).

INTRODUCTION

The stratigraphic subdivision of the Quaternary deep-sea record is not only of significance to stratigraphers but also to those who seek to understand processes that are recorded in these sediments: for example, climatic change and its causes, ocean chemistry and its variation through time, the phenomena of faunal and floral evolution and extinction, and many others. In these investigations it is often advantageous to subdivide time with an accuracy of as little as a thousand years, a degree of accuracy that is unheard of in the remainder of the stratigraphic column. Within the context of this requirement, we have worked since the IXth INQUA Congress (Christchurch, New Zealand, 1973) to establish the stratigraphic relationships between various tools available for the Quaternary.

Our strategy has been to deal primarily with what are known as *datum levels* (or *biohorizons*), and to investigate the geographic extent of each and the evidence for their synchrony or diachrony. We have promoted exchange of material and information so that datum levels could be intercalibrated in the same core material. The importance of this approach may be illustrated by the extinction levels of the radiolaria *Stylotractus universus* Hays and the calcareous nannoplankton *Pseudo-emiliania lacunosa* (Kamptner). The age of extinction of the former taxon was estimated several years ago at 350,000 to 400,000 yr in the Pacific (Hays *et al.*, 1969; Hays and Ninkovich, 1970) and Antarctic (Hays and Opdyke, 1967), whereas that of the latter taxon was estimated to be 275,000 yr (Gartner, 1972), 350,000 yr (Gartner, 1973), and 400,000 yr (Gartner and Emiliani, 1976) on the basis of work in the Atlantic and the Pacific, the different ages being due to the evolving correlation of the magnetic, radiometric, and oxygen-isotope time scales. It was recognized early that the two datum levels occurred very close to one another in the Pacific and it is now known that the extinction of *P. lacunosa* occurs stratigraphically below that of *S. universus* in both oceans as well as the Indian Ocean. Comparison with oxygen-isotope stratigraphy has shown that both extinctions occurred within an interval of only a few thousand years at most over their geographic ranges.

We have examined most of the biostratigraphic datums which are younger than about one million years in relation to now well-established magnetostratigraphy (Mankinen and Dalrymple, 1979) and oxygen-isotope stratigraphy (Shackleton and Opdyke, 1973, 1976). For early Quaternary time (pre-Jaramillo event; ca. 0.9–1.7 my), oxygen-isotope stratigraphy is less useful for datum-level correlation. However, datum levels are well intercalibrated with the magnetostratigraphy for this same interval. In all we provide information for nearly 40 biostratigraphic datum levels.

The 23 subdivisions (stages) based on oceanic oxygen-isotope stratigraphy since the Jaramillo event (ca. 0.9 my) are a convenient means of subdividing the middle and late Quaternary. Oxygen-isotope stratigraphy has greatly strengthened the correlation and chronologic value of biostratigraphic datums.

METHODS

Three different approaches can be applied to the development of a time scale for Quaternary deep-sea sediments. These are: (a) *dates*, relative to the present day; (b) *scales*, comprising a sequence of alternating conditions; and (c) *datum levels*, representing unique events in progressive faunal and floral evolution. Each of these types of evidence has different properties.

Dates provide an estimate in years of the time of formation and deposition of deep-sea sediments. Their reliability (accuracy and precision) depends on an understanding of the processes and rates of processes on which they depend, such as sediment deposition, mixing, and diagenesis, and on preparatory and analytical procedures

adopted in the laboratory. They *alone* can provide an age in years for sediment sequences. The availability of such dates has inhibited the development of the Quaternary time scale and correlations with the terrestrial Quaternary record.

Scales can be obtained from series of alternating or continuously varying parameters that form a distinctive stratigraphic pattern in marine sequences. Dates can be obtained for particular levels within the scales. Confidence in the dates increases with repetition of results. In general, however, scales obtained from these patterns are intrinsically elastic, and ages applied to them are not fixed whether they are based upon interpolation or extrapolation from dated levels.

The principal scales used in correlating and dating deep-sea sediments include:

(ii) magnetostratigraphy;

(ii) the oxygen-isotope scale (stages 1 to 23), extending from the present day to the Jaramillo Magnetic-reversal event (t = ca. 0.9 my);

(iii) calcium carbonate-content curves available for the equatorial Pacific to the Jaramillo Magnetic-reversal event;

(iv) microfossil-assemblage changes either exhibited as original frequency data, factor analysis, or transfer functions, such as used in CLIMAP studies;

(v) planktonic-foraminiferal-coiling scales, available in certain parts of the oceans.

Correlation between these various scales is best established by their concurrent determination on individual cores on which the magnetic-reversal chronology has been ascertained. It should be noted, however, that ages of all levels except magnetic reversals have been assigned by interpolation and extrapolation and hence are subject to change.

Datum levels mainly define the initial (FAD, first-appearance datum) and terminal (LAD, last-appearance datum) occurrence of the stratigraphic ranges of taxa in the progressive evolution of oceanic biota.

They need to be checked against either dates or scales for synchrony, but otherwise they are unique as biologic events. Once the paleoenvironmental, migratory, or evolutionary control of a datum has been established, it can be used to identify specific levels of a scale. Ages are applied to particular datum levels by direct dating, or more often by extrapolation or interpolation from the magnetic-polarity time scale or through another scale, such as the oxygen-isotope scale or the dissolution scale for which the ages were originally obtained from the magnetic-polarity time scale. As the ages for most scales are still determined by interpolation, the accuracy of ages of datum levels may be quite spurious.

The principle sources of datum levels in Quaternary deep-sea sediments are based upon the appearances, acmes, and extinctions of

(i) calcareous nannoplankton,

(ii) diatoms,

(iii) planktonic foraminifera,

(iv) radiolarians.

In general, the stratigraphic subdivision of the Quaternary which we propose is based upon:

(1) the oxygen-isotope scale (from 0 to ca. 0.9 my);

(2) the magnetic-reversal scale (from 0.73 to ca. 2.47 my).

The two scales effectively overlap in the interval 0.7 to 0.9 my. Ages are attributed to the magnetic-reversal scale by K/Ar dating, and to the oxygen isotope scale by interpolation from the magnetic-reversal scale. Further interpolation in both scales is used to obtain ages of specific datum levels. The accuracy of both the ages of the scale and the datum levels is thus uncertain and is expected to change with additional dates and improvements in interpolations. Radiometric dates and magnetic-reversal stratigraphy provide a reliable means of correlating marine with terrestrial deposits. Unfortunately, the oxygen-isotope scale cannot be applied to terrestrial sequences.

OXYGEN-ISOTOPE SCALE

It is now well known that the oxygen-isotopic composition of the oceans during the Quaternary underwent quasi-cyclic variation as changing quantities of isotopically light water were stored as continental ice sheets. The isotopic variations were experienced in all ocean water masses essentially synchronously, the limit being the mixing time of ocean waters which is on the order of 1000 yr. The oxygen-isotopic composition of calcareous foraminifera and coccoliths and of siliceous diatoms, varies in direct proportion to that of the water; although temperature also has a slight effect on the isotopic composition of the calcite and silica, it is nearly always possible to recognize the major features in the record of ocean isotopic changes by analyzing fossils from sediment cores. In high-sedimentation-rate areas it may be possible to recognize and correlate events in the ocean isotopic record as short as 1000 yr, particularly if it is possible to analyze benthonic foraminifera and so eliminate temperature uncertainties.

For practical stratigraphical purposes, the isotopic record was first divided into numbered stages by Emiliani (1955) and later extended by Shackleton and Opdyke (1973). The stage boundaries defined by these workers are nearly all centered on times of rapid isotopic change in the oceans, so that they can be easily recognized, even in the sediments that have accumulated quite slowly.

In this scheme (Fig. 1) odd-numbered stages (starting from Stage 1, the unfinished stage containing recent sediments) are characterized by lighter oxygen-isotope values (less continental ice) and even-numbered stages by heavier oxygen-isotope values (more continental ice). The Brunhes/Matuyama magnetic-reversal boundary is found in Stage 19[2] sediment,

[2] In core V28-239 (Shackleton and Opdyke, 1976) it is shown as occurring at the Stage 19/20 boundary (in text) and (erroneously) in Stage 20 in Figure 1 (Fig. 1 of this paper shows its proper placement).
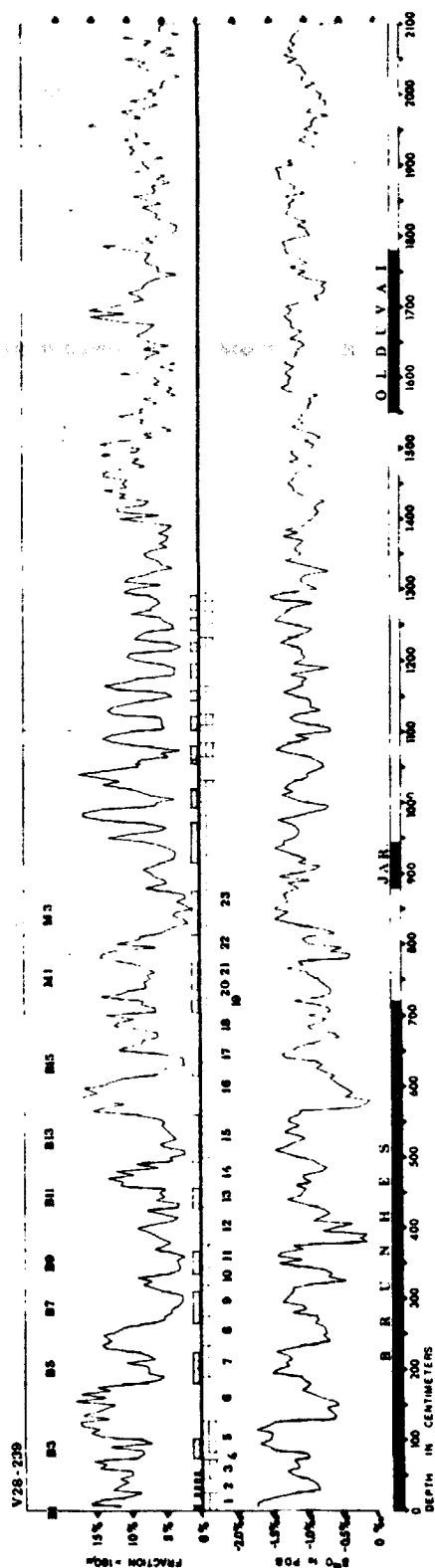

FIG. 1. Coarse-fraction record (above), oxygen-isotope record (below), and paleomagnetic record in core V28-239. Reproduced, with permission, from

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and the magnetic-reversal boundary marking the top of the Jaramillo magnetic event is found in Stage 23 sediment. Stage 23 is the oldest so far defined: Shackleton and Opdyke (1976) considered that since the isotopic fluctuations prior to that were of higher frequency, and probably of lower amplitude, they would be substantially less useful as a stratigraphic tool, although van Donk (1976) numbered stages to 41. Comparison between the low-accumulation-rate Atlantic core V16-205 studied by van Donk and the rather higher-accumulation-rate core V28-239 studied by Shackleton and Opdyke (1976) supports the notion that the use of the oxygen-isotope record as a high-resolution stratigraphic tool should be restricted at present to the 23 stages extending to the Jaramillo magnetic event or to about 0.9 my. Future work on cores with high rates of sedimentation may enable the system to be extended to the base of the Pleistocene.

Shackleton (1969) subdivided Stage 5 into five substages lettered a to e in the same direction (from younger to older) as the direction in which the stages are numbered (contrary to the reading of Suggate (1974)). Ninkovich and Shackleton (1975) subdivided Stage 7 into three substages a to c. It seems likely that an interglacial vegetational succession, as implied by the zonation of pollen diagrams discussed, for example, by Turner and West (1968), took place within about the time taken to deposit one substage. For example, Shackleton (1969) argued that the Ipswichian interglacial, as defined by its vegetational succession, should be approximately correlated with substage 5e.

The stage boundaries may formally be regarded (at least at the present time) as being defined by their placement in core V28-238 (curated in the Lamont–Doherty Geological Observatory, Columbia University, Palisades, N.Y.). Extensive coccolith, foraminiferal, and radiolarian stratigraphic work has been performed on this core, although unfortunately it does not contain sufficient diatoms for useful stratigraphic work.

In cores covering a wide latitudinal range in all oceans, oxygen-isotope sequences have been used to assess the degree to which biostratigraphic datum levels have the same age in different regions, as discussed elsewhere in this report.

MAGNETIC-REVERSAL SCALE

Almost all the information that we have concerning the age of Pleistocene marine sediments is based either directly or indirectly on the magnetic-polarity time scale which rests, in turn, upon the K/Ar dating of terrestrial lavas.

Unfortunately the best K/Ar dates are subject to errors of about 5% so that it is difficult, using one determination, to define sharply a magnetic transition; however, if many measurements are available for lavas near a magnetic boundary, then it is possible to date that boundary more precisely (Cox and Dalrymple, 1967). This has now been done for three major magnetic boundaries.

Mankinen and Dalrymple (1979) have redetermined the age of the Brunhes/Matuyama transition and find that the best estimate is 0.7 my. The precise placement of this boundary in time is complicated by the fact that the Jaramillo event occurs within 150,000 yr of the transition. McDougall and Aziz-ur-Rahman (1972) have redetermined the Matuyama/Gauss transition and place it at about 2.47 ± 0.04 my.[3] The Gauss/Gilbert transition is also well determined at 3.40 my (Mankinen and Dalrymple, 1979). Dating of these three transitions forms the basis for dating intervening polarity events, and together they have made possible extrapolation of the magnetic-polarity time scale for the entire Cenozoic (Heirtzler et al., 1968). Unfortunately, the precision of the K/Ar method is not good enough to allow independent de-

[3] Recalculated by Mankinen and Dalrymple (1979) due to change of K/Ar decay constants.

terminations of the magnetic transitions associated with events. The age and duration of events, as distinct from their approximate placement in time, must therefore be based on other techniques. The difficulty of dating such transitions has been well illustrated by the controversy over the Olduvai and Gilsa events, which has been extensively reviewed by Watkins (1972) and Opdyke (1972) and will not be pursued further.

Cox, in creating his widely quoted time scale published in 1969, recognized this problem and chose to utilize the information gleaned from sea-floor-spreading anomalies to help solve it. In optimum cases where a ridge is continuously spreading, the sea-floor basalts act as a continuous magnetic tape recorder faithfully recording the reversals of the earth's magnetic field. After the anomalies are identified and correlated with the time scale, a model may be created from which the age and duration of the events can be

determined. This technique should, however, be applied to several different profiles since complicating circumstances exist, such as discontinuous spreading, ridge jumping, and unrecognized fracture zones. These problems introduced a certain amount of subjectivity into the results, which is difficult to avoid.

A second way of determining the length and duration of events is derived from studies of marine sediments. In this case, the sediments are believed to record continuously the changing polarity of the earth's magnetic field as the sediments accumulate. The age and duration of the events are then determined by extrapolating rates of sedimentation from known reversal transitions or by interpolating between magnetic transitions. This technique has been used by Opdyke (1972). Like the determinations derived from sea-floor spreading, this method suffers from the assumption that the rate of sedimentation is

TABLE 1

GEOMAGNETIC TIME SCALE

Klitgord et al. (1975)		This paper [a]	
Anomaly	Age (my)	Normal interval	Age (my)
Central	0.00		0.00
	0.73 ± 0.03 [b]	Brunhes	0.73
1'	0.92 ± 0.04	Jaramillo	0.88 ± 0.02
	0.98 ± 0.05		0.94 ± 0.03
2	1.67 ± 0.03	Olduvai	1.72 ± 0.04
	1.88 ± 0.03		1.88 ± 0.04
2'.1	2.47 ± 0.04 [b]	Upper Gauss	2.47
	2.91 ± 0.04		2.88
2'.2	2.98 ± 0.01	Middle Gauss	2.96
	3.07 ± 0.01		3.07
2'.3	3.17 ± 0.02	Lower Gauss	3.16
	3.40 ± 0.02 [b]		3.40
3.1	3.94 ± 0.01	Cochiti	3.87
	4.04 ± 0.01		3.97
3.2	4.15 ± 0.01	Nunivak	4.10
	4.26 ± 0.01		4.24
3.3	4.37 ± 0.01	C_1	4.39
	4.43 ± 0.01		4.46
3.4	4.56 ± 0.01	C_2	4.56
	4.79 ± 0.01		4.76

[a] Ages modified from Mankinen and Dalrymple (1979).
[b] Ages determined from rock paleomagnetic data and K/Ar dating.

constant. Therefore, subjectivity as to which cores are selected is introduced, of necessity, by the observer. However, if sufficient profiles and cores are used, then an approximation of the true age is approached.

Table I shows a comparison of the results of these two techniques using the recent determinations of Klitgord *et al.* (1975) and an updated version of the data presented in Opdyke (1972). Both sets of data are derived by using the K/Ar-derived ages of 0.7, 2.41, and 3.32 my for the epoch boundaries, based on the old decay constant. It can be seen that the results of the two methods are remarkably similar. The largest discrepancy between the two methods appears to be the onset of Jaramillo event 40,000 yr later in the anomaly time scale (0.89 instead of 0.85 my) than in the core-derived time scale. The only other significant difference is in the length of the Olduvai event which appears longer in the sea-floor-spreading data by about 50,000 yr. The errors in both techniques are such as to make the differences hardly significant. What is abundantly clear is that both recording systems are detecting simultaneous changes in the earth's magnetic field.

EVENTS

It should be noted that in both techniques the shortest event that can consistently be detected and dated is the Jaramillo event, about 60,000 yr in length. An event such as the Reunion event, which is said to occur about 2.1 my (McDougall and Watkins, 1973), has a duration of only 10,000 yr. Unfortunately at the type locality on Reunion Island the Olduvai event is not seen. A small anomaly is sometimes seen in the sea-floor-spreading record at about this time (Heirtzler *et al.*, 1968; Emilia and Heinrichs, 1969, 1972), so the existence of this very short event or events may be real. Attempts to detect this event in marine sediments with rates of sedimentation on the order of 1 cm/1000 yr have not met with success.
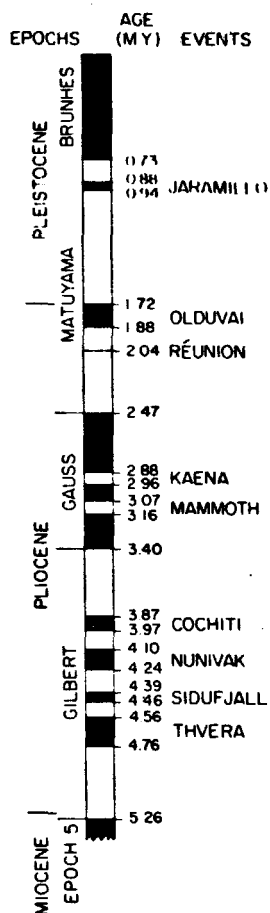

FIG. 2. Ages of magnetic-reversal epoch boundaries and events as attributed in Figures 3–5.

CALCAREOUS NANNOPLANKTON DATUM LEVELS

The calcareous nannoplankton biostratigraphic and biochronologic framework of the Pleistocene was established by Gartner (1969, 1972; Gartner and Emiliani, 1976). Two important datum levels were recognized in the Upper Pleistocene, i.e., the LAD of *Pseudoemiliania lacunosa* and the FAD of *Emiliania huxleyi,* which were shown to have occurred within oxygen-isotope Stages 12 and 8, respectively (Gartner, 1972) (Figs. 3, 4).

The global synchrony of the LAD of *P. lacunosa* and the FAD of *E. huxleyi* have recently been established in seven deepsea cores underlying tropical, subtropical, tran-
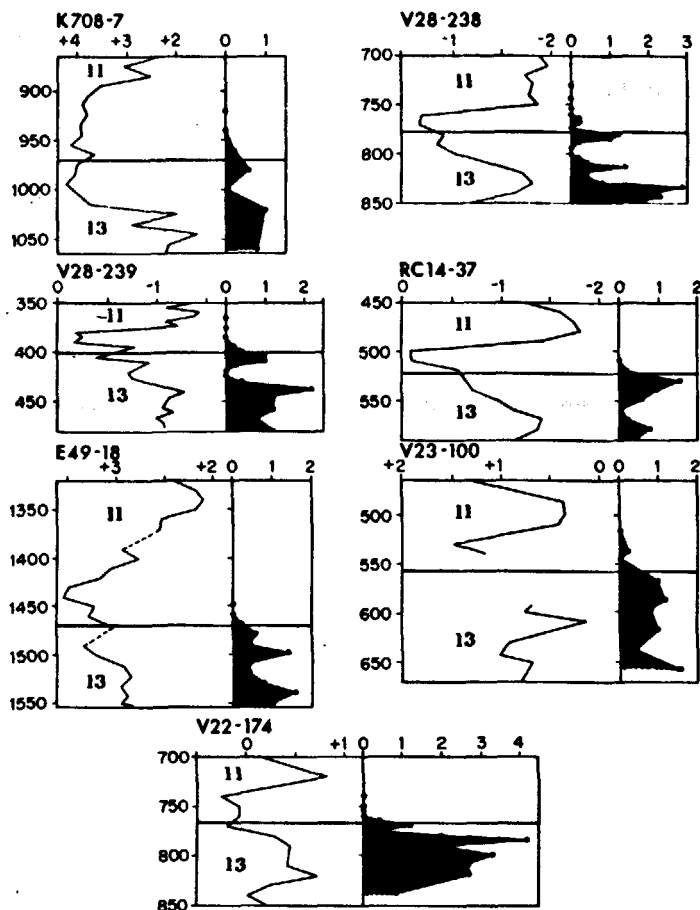
FIG. 3. On the left, oxygen-isotope ratios for Stages 11, 12, and 13. On the right, relative abundances of *P. lacunosa* given as percentages. Both are plotted to depth (centimeters) in core. The solid horizontal line indicates the position of the *P. lacunosa* extinction level. Reproduced, with permission, from Thierstein *et al.* (1977, Fig. 1).

sitional, and subpolar waters by correlation between the oxygen-isotope and paleomagnetic-stratigraphic record (Thierstein *et al.*, 1977) (Figs. 3–5). The LAD of *P. lacunosa* is within isotope Stage 12 (ca. 474,000 yr) and the FAD of *E. huxleyi* consistently occurs within isotope Stage 8 (ca. 275,000 yr). A third calcareous nannoplankton datum is the reversal in dominance of *Gephyrocapsa caribbeanica* and *Emiliania huxleyi* which, although shown to be time transgressive (occurring some 12,000 yr earlier in low latitudes), consistently occurs in oxygen-isotope stage 4 in transitional waters (ca. 73,000 yr). In tropical and subtropical waters it is associated with isotope Substages 5b–5a (ca. 85,000 yr) (Figs. 4, 5).

The sequential initial appearance of early members of the *Gephyrocapsa* lineage (*G. aperta, G. caribbeanica,* and *G. oceanica*) has been found biostratigraphically useful in the vicinity of the Olduvai event in tropical and subtropical Atlantic and Pacific deep-sea cores as well as the Pliocene/ Pleistocene boundary in the Mediterranean (Haq *et al.*, 1977a). The FAD of *G. aperta* occurs at about 2.36 my. The FAD's of *G. caribbeanica* and *G. oceanica* bracket the top of the Olduvai event at ca. 1.74 and 1.68 my, respectively.

Examination of three DSDP cores (Sites 154A, 206, and 289) from the Caribbean, northern Tasman Sea, and western Equatorial Pacific has resulted in a further biochronologic subdivision of the Pleistocene
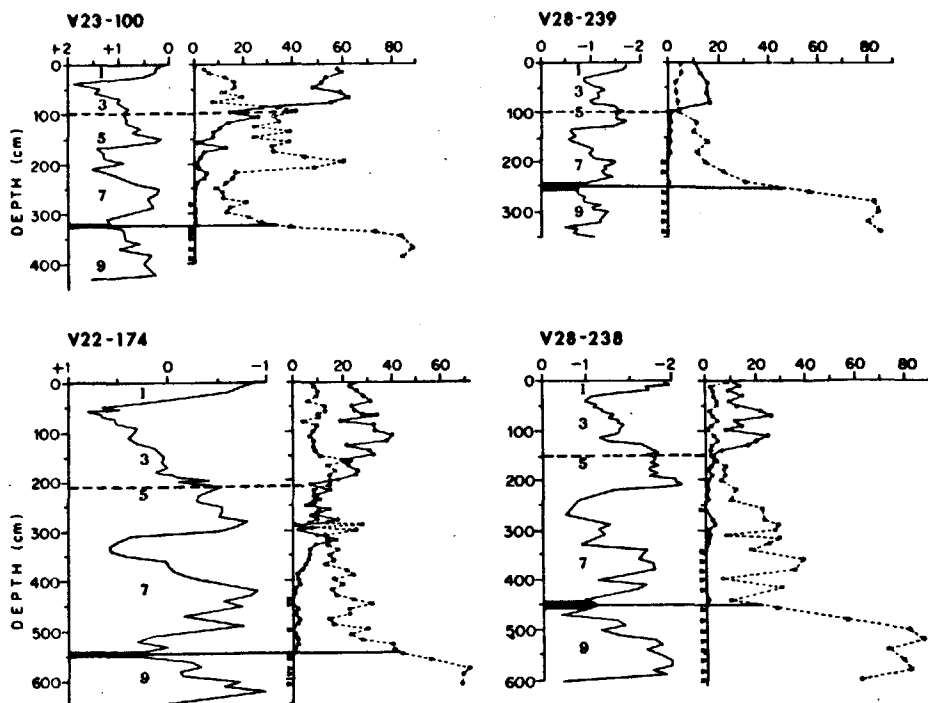
FIG. 4. Low-latitude tropical and subtropical cores. On the left, oxygen-isotope ratios plotted through Stage 9; on the right, relative abundances of *E. huxleyi* (solid line) and *G. caribbeanica* (broken line) given as percentage of total calcareous nannoflora. Both are plotted to depth (centimeters) in core. Solid triangles indicate samples where *E. huxleyi* is absent: The solid horizontal line indicates the positions of the *E. huxleyi* first-appearance level; the dashed horizontal line indicates the position of the *G. caribbeanica/E. huxleyi* dominance-reversal level. Reproduced, with permission, from Thierstein *et al.* (1977, Fig. 2).

based on calcareous nannoplankton (Gartner, 1977; Gartner, 1973) (Fig. 6). Several datum levels have been established (in addition to those discussed above) and estimated ages have been assigned based on interpolation after correlation between the DSDP cores and paleomagnetically "dated" piston cores. These datum levels are (from top to bottom):

TABLE A

Datum	Age (my)
(1) LAD of "small Gephyrocapsa"	0.90
(2) LAD of *Helicopontosphera selii*	1.25
(3) LAD of *Cyclococcolithina mcintyrei*	1.62
(4) LAD of *Discoaster brouweri*	1.77

The LADs of "small *Gephyrocapsa*" and *Discoaster brouweri* correspond to the top of the Jaramillo event and to a level near the top of the Olduvai event, respectively. The "LAD" of "small *Gephyrocapsa*" is not strictly speaking a LAD, but rather it marks the top of the interval of dominance of small *Gephyrocapsa* (several species) and the virtual absence of *Gephyrocapsa oceanica*, which species is, however, present both above and below this interval (Fig. 7). The LAD of *C. mcintyrei* is only slightly subsequent to the top of the Olduvai event. The relationship of calcareous nannofossil zones to oxygen-isotopic stratigraphy is shown in Figure 8.

DIATOM AND SILICOFLAGELLATE DATUM LEVELS

Eight diatom and two silicoflagellate datum levels have been correlated to the paleomagnetic time scale and, by second-
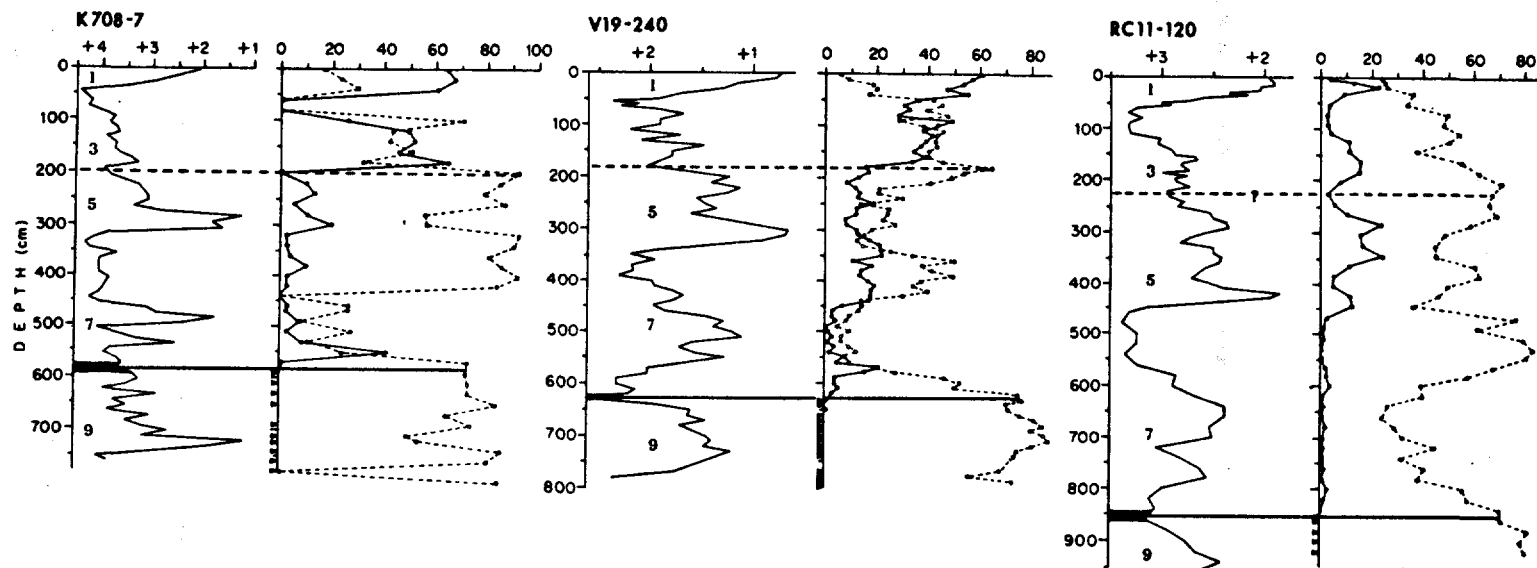
FIG. 5. High-latitude transitional and subpolar cores. Additional explanation as in Figure 4. In RC11-120, the question mark indicates the presumed *G. caribbeanica/E. huxleyi* reversal datum level. Reproduced, with permission, from Thierstein *et al.* (1977, Fig. 2a).
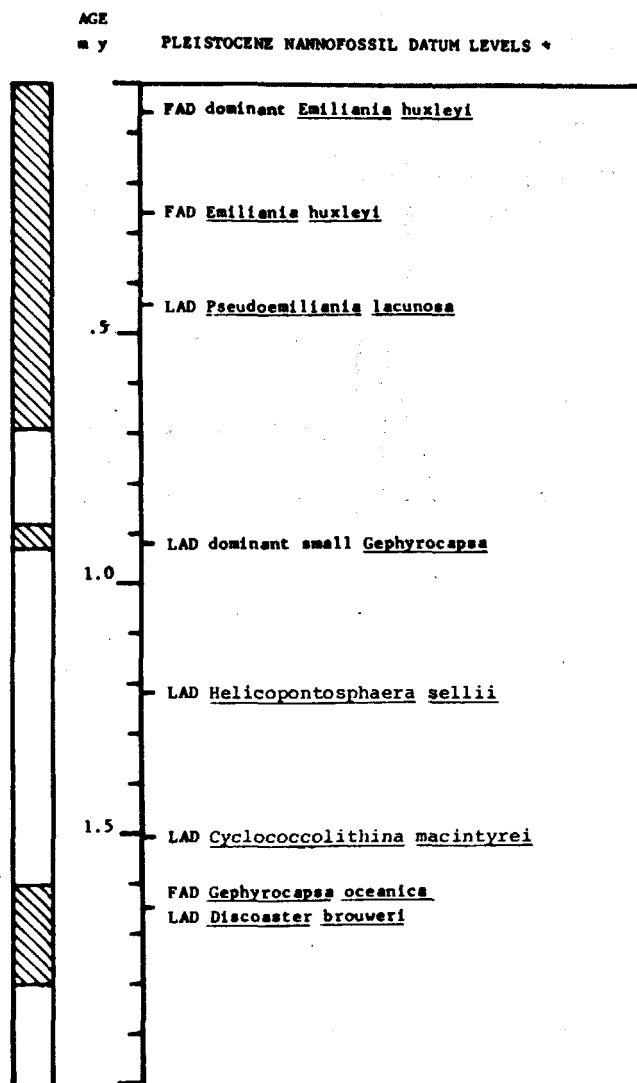
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AGE
m y   PLEISTOCENE NANNOFOSSIL DATUM LEVELS ↵

- FAD dominant Emiliania huxleyi

- FAD Emiliania huxleyi

- LAD Pseudoemiliania lacunosa

.5

- LAD dominant small Gephyrocapsa

1.0

- LAD Helicopontosphaera sellii

1.5 - LAD Cyclococcolithina macintyrei

- FAD Gephyrocapsa oceanica
- LAD Discoaster brouweri

FIG. 6. Pleistocene calcareous nannofossil datum levels (compiled from Gartner and Emiliani (1976) and Gartner (1977). FAD, first-appearance datum; LAD, last-appearance datum.

order correlation, to the oxygen-isotope record for the interval late Pliocene – Holocene, ca. 2.7 my to the present (Burckle, 1977) (Figs. 9 – 11). These datum levels have been given a numerical hierarchical ranking of reliability (based on ease of identification of taxa, relative ubiquity, and rapidity of appearance or extinction). These are shown below in Tables 2, 3.

PLANKTONIC FORAMINIFERAL DATUM LEVELS

Latest Pliocene and Pleistocene planktonic foraminiferal datum levels include in ascending order (Figs. 12, 13):

(1) LADs of *Globorotalia miocenica* and *G. exilis* in tropical Atlantic cores at approximately 2.2 and 2.0 my, respectively (Briskin and Berggren, 1975; Saito *et al.*, 1975);
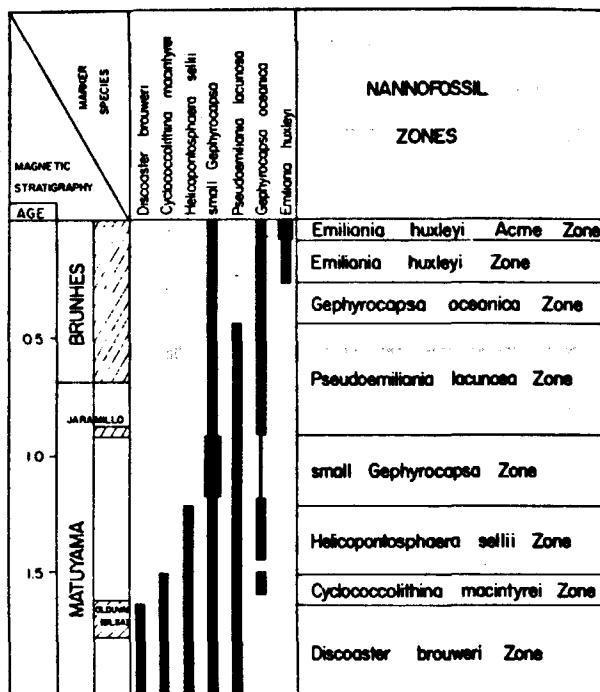
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FIG. 7. Revised nannofossil zonation of Pleistocene pelagic sediments of tropical and temperate regions. Reproduced, with permission, from Gartner (1977, Fig. 5).

(2) FAD of *Globorotalia trun-catulinoides* just below the base of the Old-uvai (ca. 1.9 my) in subtropical and mid-latitude cores in Atlantic (Berggren *et al.*, 1967; Phillips *et al.*, 1968) and Pacific (Hays and Berggren, 1971; Saito *et al.*, 1975; Haq *et al.*, 1977b). (in V28-239 (Shackleton and Opdyke, 1976) the FAD of *G. trun-*
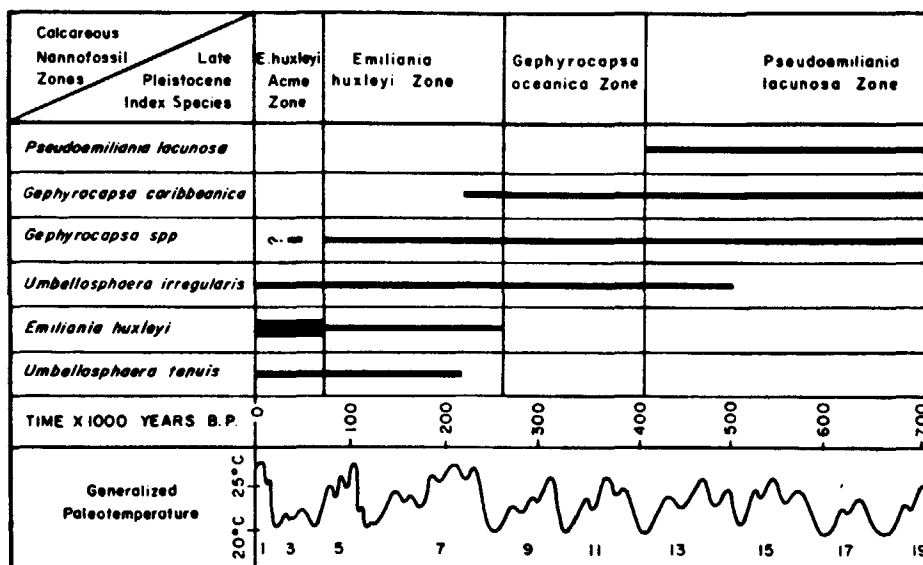

FIG. 8. Nannofossil zonation related to oxygen-isotope stages. Reproduced, with permission, from Gartner and Emiliani (1976, Fig. 1).
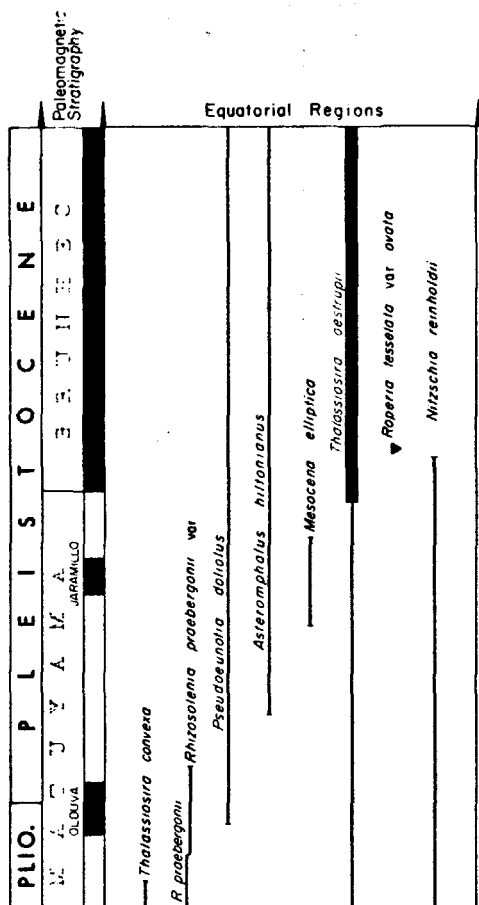
FIG. 9. Late Pliocene and Pleistocene diatom datum levels for the Equatorial Pacific. Termination of a line indicates first or last appearance of a species. The "dig leg" in the range of *Rhizosolenia praebergonii* marks the first appearance of the variant of this species. The change in thickness of a line (as in *Thalassiosira oestrupii*) represents an upward increase in the abundance of this species. The inverted triangle by *Roperia tesselata* var. *ovata* marks the peak occurrence of this species.
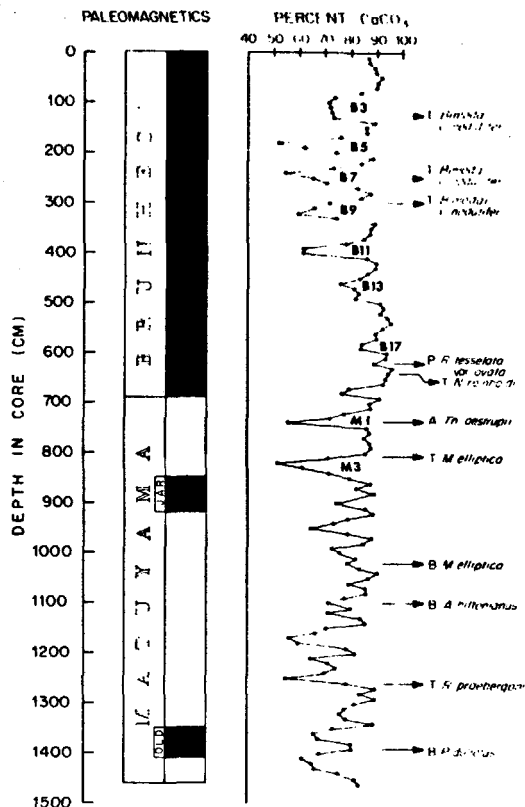

FIG. 10. Correlation of diatom datum levels and calcium carbonate fluctuations in TC11-209. Terminology for carbonate minima is taken from Hays *et al.* (1969). The letter code in front of each species is as follows: B., first appearance of a species; T., last appearance of a species; A., first abundant appearance; P., a marked but brief abundance occurrence (peak).

catulinoides occurs within an unnumbered low-amplitude "interglacial" 10 cm below the base of the Olduvai (Haq *et al.*, 1977));

(3) LADs of *Globigerinoides obliquus* and G. fistulosus in tropical and subtropical Atlantic and Pacific cores at the top of the Olduvai (1.7 my) and just above the Olduvai (1.6 my), respectively.

In addition to the above there is a series of datum levels associated with coiling changes in the genus *Pulleniatina* (Saito,

1976) in the Indo-Pacific. After its disappearance in the Atlantic ca. 2.4 my (but with the exception of left-coiling populations just below and at the base of the Olduvai ca. 1.95 and 1.90 my, respectively) coiling changes were restricted to Pacific populations. These included in descending order (left-coiling populations) and in the terminology of Saito (1976):

L1—between Jaramillo and Brunhes/ Matuyama boundary, ca. 0.8 my;

L2—near base Jaramillo, ca. 0.95 my;

L3—between Jaramillo and Olduvani, ca. 1.45 my;

L4—upper part of Olduvai, ca. 1.75 my;
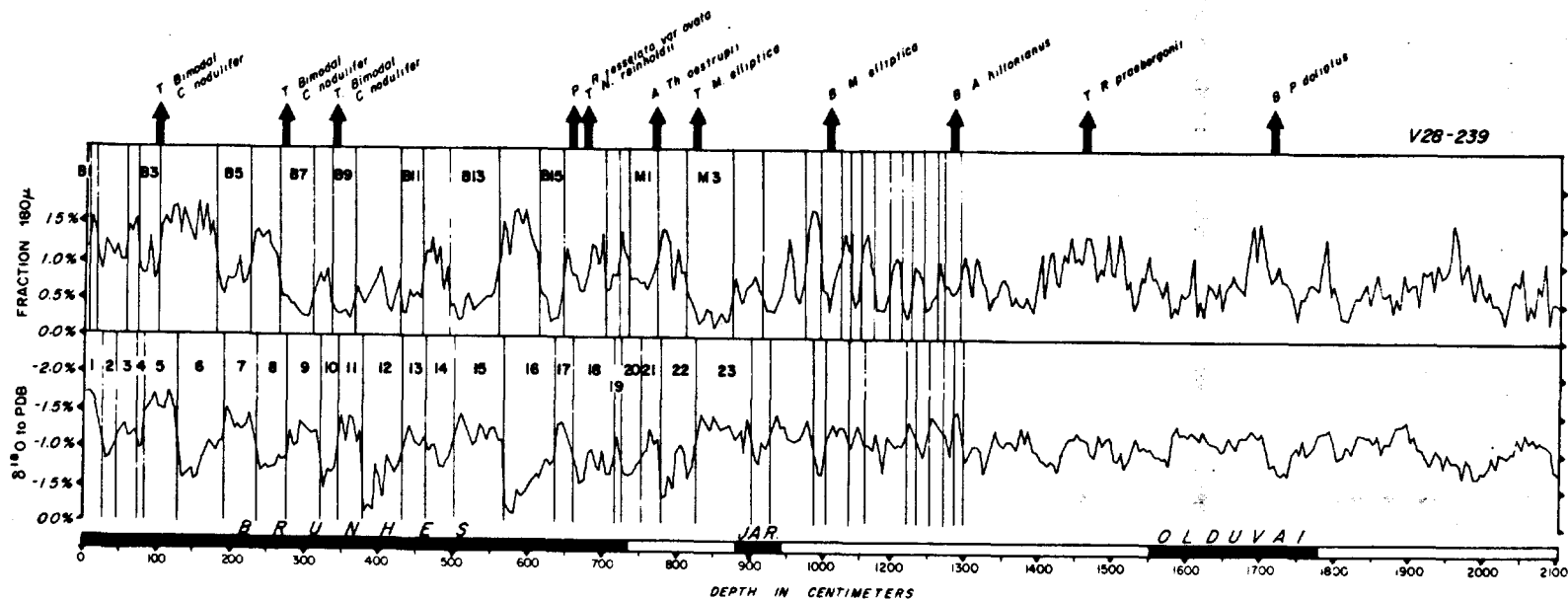
L5—base Olduvai, ca. 1.88 my.

FIG. 11. Correlation between diatom datum levels, calcium carbonate curve, and oxygen-isotope record. Notations for datum levels are described in Figure 8. The oxygen-isotope curve is for core V28-239 and is taken from Shackleton and Opdyke (1976).

TABLE 2

Late Pliocene - Pleistocene First-Order Datum Events: Diatoms and Silicoflagellates [a]

Category	Nature	Age (my)	Remarks
1	1. LAD of *Thalassiosira convexa*	2.2	Midway between Gauss/Matuyama boundary and base Olduvai in tropical and mid-latitude Pacific and Indian Oceans, North Pacific, South Pacific, and South Indian Ocean
	2. FAD of silicoflagellate *Mesocena elliptica*	1.3	Approximately midway between top Olduvai and base Jaramillo in Equatorial Pacific and Indian Oceans
	3. LAD of *Mesocena elliptica*	0.79	LAD is isochronous with oxygen-isotope Stage 22. Range of taxon brackets Jaramillo in Equatorial Pacific (Hays *et al.*, 1969) and Indian Ocean (Burckle, 1971, 1972)
	4. LAD of *Nitzschia reinholdii*	0.63	LAD in lower Brunhes in North and Equatorial Pacific; isochronous with oxygen-isotope Stage 18
	5. Peak zone of *Roperia tesselata* var. *ovata*	0.61–0.62	Short range of peak abundance in Equatorial Pacific in lower Brunhes; isochronous with oxygen-isotope Stage 17

[a] Burckle, 1977.

Finally, the LAD of *Globoquadrina pseudofoliata* has been shown to occur within oxygen-isotope Stage 7 (ca. 220,000 yr) in tropical Indo-Pacific regions (Thompson and Saito, 1974; Thompson, 1976).

ANTARCTIC–SUBANTARCTIC PLANKTONIC FORAMINIFERAL DATUM LEVELS

Examination of Quaternary piston-core sequences from the Antarctic–Subantarctic region has revealed several distinct

TABLE 3

Pleistocene Second- and Third-Order Events: Diatoms [a]

| Category	Nature	Age (my)	Remarks
2	1. Rapid size increase in *Rhizosolenia praebergonii*	2.0	Just below base Olduvai in Equatorial Pacific
	2. FAD of *Pseudoeunotia doliolus*	1.8	Near base Olduvai in tropical and intermediate latitudes of all oceans (40°N to 40°S)
	3. LAD of *Rhizosolenia praebergonii* var.	1.5	Just above top Olduvai in tropical and subtropical Indo-Pacific (possibly diachronous between high and low latitudes)
3	1. FAD of *Asteromphalus hiltonianus*	1.4	Between Olduvai and Jaramillo in Equatorial Indo-Pacific (rare), but common in upwelling areas of easternmost Equatorial Pacific
	2. Upward increase in abundance of *Thalassiosira oestrupii*	0.745	Just below Brunhes/Matuyama boundary; synchronous in Equatorial Pacific cores but relationships in Indian Ocean and higher latitudes not known; correlated with oxygen-isotope Stage 21

[a] Burckle, 1977.
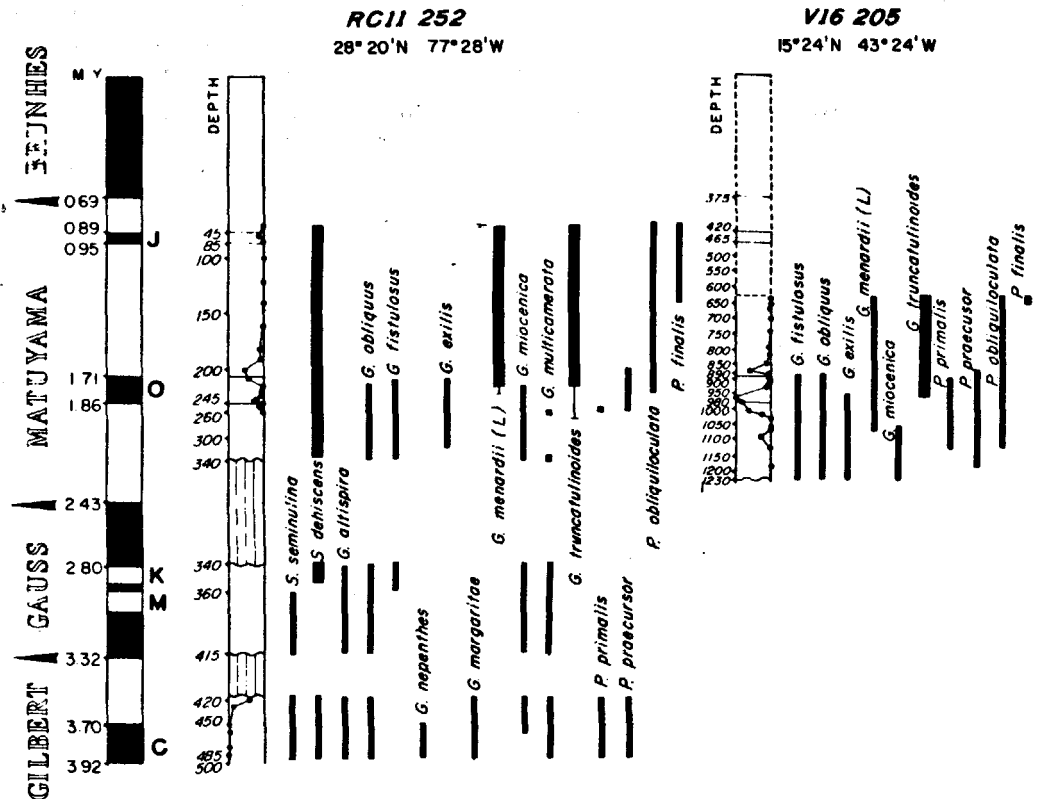
FIG. 12. Paleomagnetic stratigraphy, ranges of characteristic planktonic foraminiferal species, and coiling-ratio changes in the genus *Pulleniatina* in North Atlantic cores RC11-252 and V16-205. Coiling-ratio changes are plotted as 100% dextral on the right side and 100% sinistral on the left side. Depth in cores is given in centimeters. Horizontal lines denote geomagnetic-reversal boundaries observed in each core. Key to planktonic foraminifera: *Sphaeroidinellopsis seminulina* (Schwager), *Sphaeroidinella dehiscens* (Parker and Jones), *Globoquadrina altispira* (Cushman and Jarvis), *Globigerinoides obliquus* Bolli, *G. fistulosus* (Schubert), *Globigerina nepenthes* Todd, *Globorotalia exilis* Blow, *G. margaritae* Bolli and Bermudez, left-coiling population of *Globorotalia menardii* (Parker, Jones, and Brady), *G. miocenica* Palmer, *G. multicamerata* (Cushman and Jarvis), *G. truncatulinoides* (d'Orbigny). *Pulleniatina primalis* Banner and Blow, *P. praecursor* Banner and Blow, *P. obliquiloculata* (Parker and Jones), *P. finalis* Banner and Blow. Reproduced, with permission, from Saito *et al.* (1975, Fig. 7).

datum levels provided by first or last appearance of various planktonic foraminifera (Kennett, 1970; Keany and Kennett, 1972; Vella *et al.*, 1976; Williams, 1976). These datums, although apparently of circum-Antarctic distribution, are clearly time transgressive with first and last occurrences in lower-latitude regions. Nevertheless, they do provide important datums within the Subantarctic – Antarctic region and have been dated using paleomagnetic stratigraphy, oxygen-isotope stratigraphy, or thorium dating. These datum levels are listed as follows:

(1) first appearance (migration; nonevolutionary) of *Globorotalia truncatulinoides* and simultaneous last appearance (replacement) of *Globorotalia crassaformis*, at 270,000 to 300,000 yr within oxygen-isotope Stage 8 (Kennett, 1970; Vella *et al.*, 1976; Williams, 1976);

(2) last appearance (extinction) of *Globorotalia puncticulata* near Brunhes/ Matuyama boundary at 0.73 my;

(3) first appearance (migration; nonevolutionary) of *Globorotalia inflata* near Brunhes/Matuyama boundary at 0.73 my.
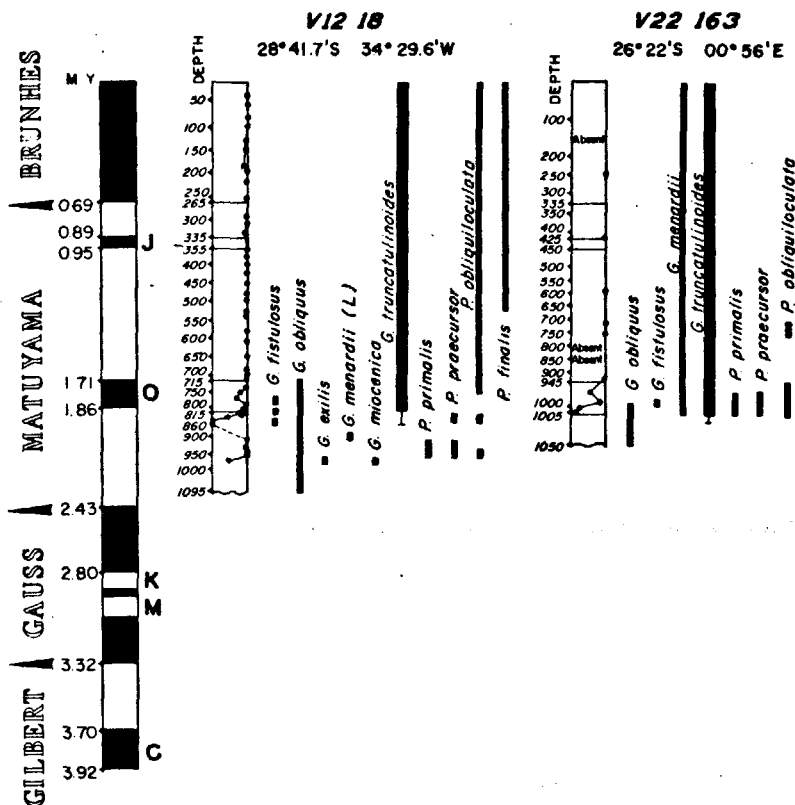
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FIG. 13. Paleomagnetic stratigraphy, ranges of characteristic planktonic foraminiferal species, and coiling-ratio changes in the genus *Pulleniatina* in South Atlantic cores V12-18 and V22-163. Coiling-ratio changes are plotted as 100% dextral on the right side and 100% sinistral on the left side. Depth in cores is given in centimeters. Horizontal lines denote geomagnetic-reversal boundaries observed in each core. See Figure 10 caption for key to planktonic foraminifera. Reproduced, with permission, from Saito *et al.* (1975, Fig. 8).

RADIOLARIA

The LAD of *Stylatractus universus* (=*Axoprunum angelinum*) occurs near the boundary of oxygen-isotope Stages 11/12 b (ca. 410,000 yr) at the base of carbonate peak B9 (Hays *et al.*, 1969) with a synchrony estimated at ca. 3000 yr between high and low latitudes (Hays and Shackleton, 1976) in six deep-sea cores ranging from the North Pacific and Equatorial Pacific to the tropical and subantarctic Indian Ocean (Fig. 14). Morley and Shackleton (1978) extended the geographic range of this synchronous extinction to the South Atlantic and Equatorial Atlantic. Correlation of this datum to the oxygen-isotope and the paleomagnetic record has shown the diachrony of this datum, suggested by Johnson and Knoll (1974), to be in error.

Several other late Pliocene and Pleistocene radiolarian datum levels have been correlated to the paleomagnetic records (Hays and Berggren, 1971) (Fig. 15). These are discussed below according to geographic distribution.

(A) *Antarctic region:* (1) The LAD of *Helotholus vema* and *Desmospyris spongiosa* coincides with the Gauss/Matuyama boundary at ca. 2.4 my (Hays and Berggren, 1971); (2) the LAD of *Eucyrtidium calvertense* and *Clathrocyclas bicornis* occurs near the base (1.9 my) and top (1.72 my) of the Olduvai event, respectively.

(B) *North Pacific:* (1) The virtually synchronous LAD of *Lamprocyclas heteroporos* and FAD of *Eucyrtidium matuyamai* occur in the lower part of the
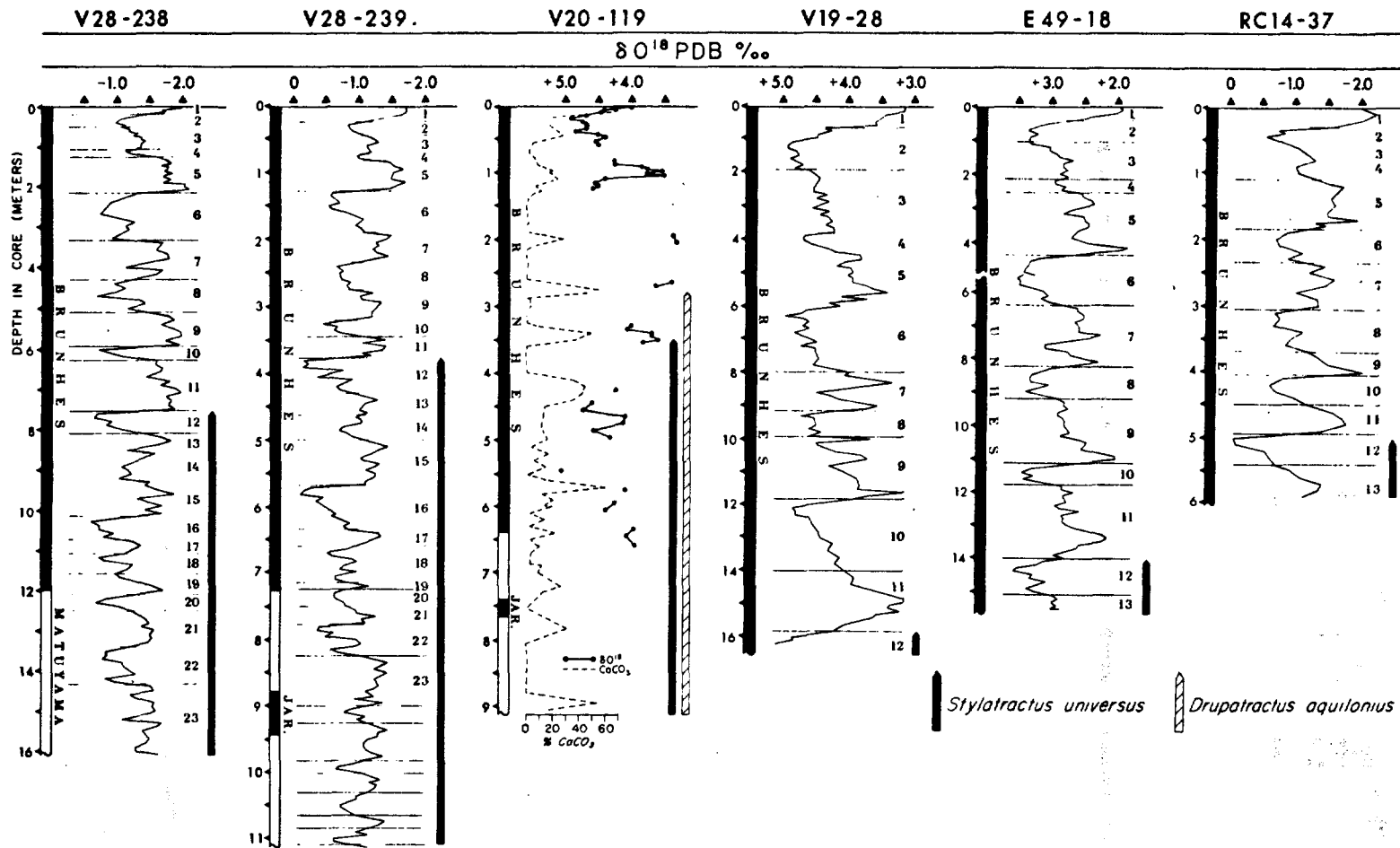
FIG. 14. Range of *Stylatractus universus* in six cores studied. Black and white bars in cores V28-238, V28-239, and V20-119 indicate published magnetic stratigraphy data (inferred normal in remaining three cores). Oxygen-isotope records show analyses of *Globigerinoides sacculifer* (cores V28-238, V28-239, RC14-37), *Uvigerina* sp. (cores V20-119, V19-28), and *Globigerina bulloides* (core E49-18). Percentage CaCO₃ also plotted for core V20-119, in which δO¹⁸ record is discontinuous due to absence of foraminifera in sections with very low CaCO₃. In core V20-119, solid lines with circle ends = δO¹⁸, dashed line = CaCO₃. Reproduced, with permission, from Hays and Shackleton (1976, Fig. 1).
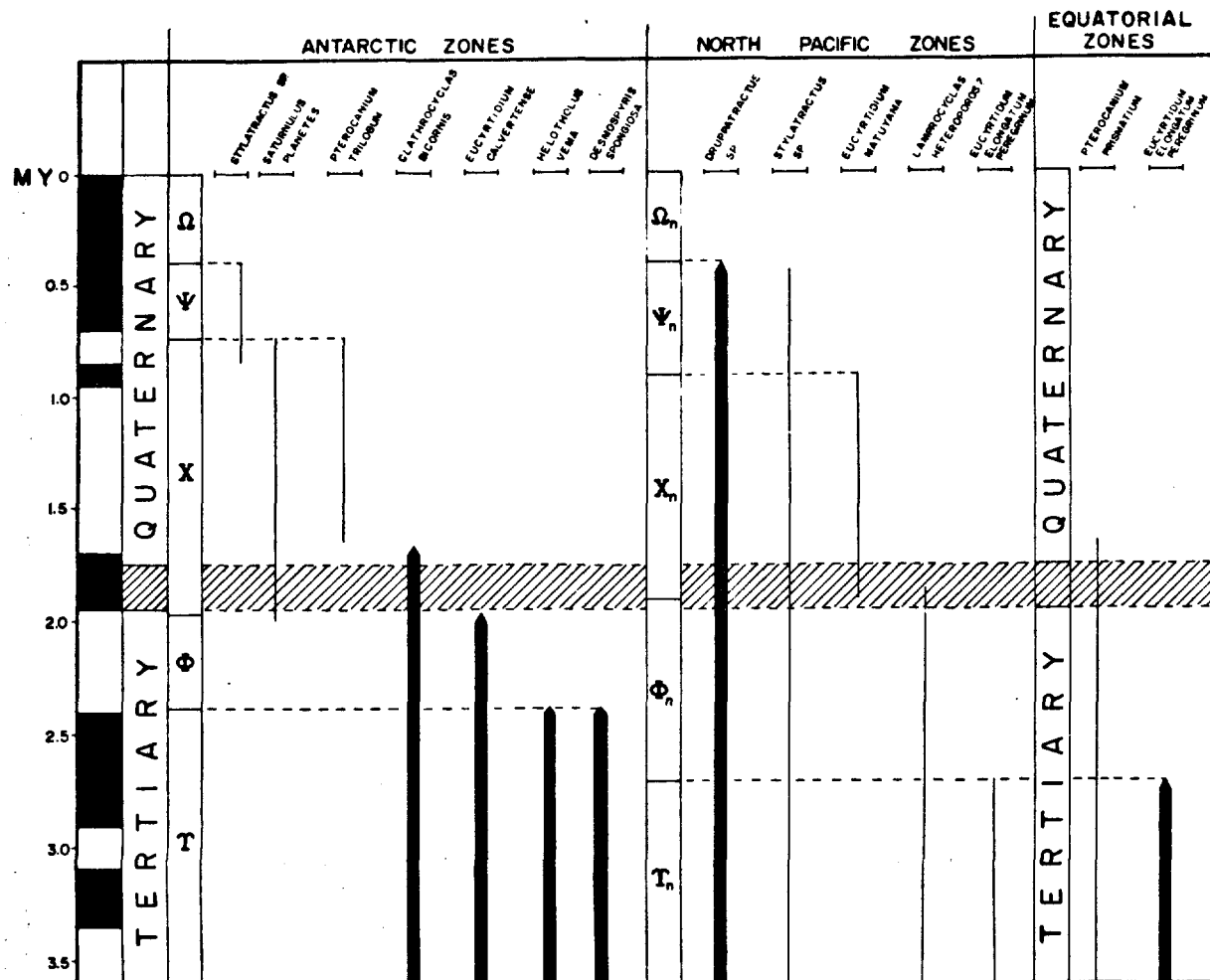
FIG. 15. Long-range correlation of Antarctic, North Pacific, and Equatorial Pacific radiolarian zones and their relationship to the Pliocene/Pleistocene boundary. Reproduced, with permission, from Hays and Berggren (1971, Fig. 8).

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Olduvai event (ca. 1.83 my); (2) the LAD of *E. matuyamai* occurs in the lower part of the Jaramillo event (ca. 0.9 my).

(C) *Equatorial Pacific:* The LAD of *Pterocanium prismatium* occurs just above the Olduvai event (ca. 1.7 my).

SUMMARY

— In the belief that an intra-Quaternary (bio)chronology is best founded upon the (bio)stratigraphic record in deepsea sediments, we have correlated over 40 biostratigraphic datum levels to the geomagnetic-reversal scale and several datum levels to the oxygen-isotope stratigraphy. These two iterative stratigraphies have in turn been calibrated to an ordinal geochronology, the radiometric time scale, thus providing a means of critically investigating the extent to which such events are synchronous or diachronous over the geographic extent of their distribution. Figures 16 and 17 illustrate the datum levels correlated to the magnetic scale and oxygen-isotope stratigraphy, respectively. This represents the chronologic subdivision (time scale) of the Quaternary which we propose based upon the calibration of biostratigraphic datum levels (events) to: (1) oxygen-isotopic scale (from 0 to ca. 900,000 yr) and (2) the magnetic-reversal scale (from 0.73 to ca. 2.47 my). The two scales overlap in the interval of 700,000 to 900,000 yr ago. Future work in this direction will be aimed at refining the (bio)chronology established here by correlating as many datum levels as possible to the oxygen-isotope stratigraphy. —

APPENDIX: TIME-SCALE BASES AND LEVELS

1. Interscale correlation is based on core V28-239 from the western Equatorial Pacific on which determinations of oxygen-isotope, magnetic-reversal, and carbonate-dissolution (coarse-fraction preservation) scales were made (Fig. 1) (Shackleton and Opdyke, 1976).

2. Ages on the oxygen-isotope scale are based on a date of 730,000 yr for the Brunhes/Matuyama magnetic reversal in core V28-238, and linear interpolation assuming a sedimentation rate of 1.64 cm/1000 yr (Shackleton and Opdyke, 1973, 1976).

3. Dating of the magnetic-reversal scale is based on ages of 0.73 my for the Brunhes/Matuyama reversal, and 0.88 and 0.94, and 1.72 and 1.88 for the tops and bottoms of the Jaramillo and Olduvai events, respectively.

4. Ages on the carbonate-dissolution scale are based on comparison with the oxygen-isotope scale (Shackleton and Opdyke, 1976).

5. *Emiliania huxleyi* becomes more abundant than *Gephyrocapsa caribbeanica* in ^{18}O Stage 4 in transitional waters (K708-7, V19-240, RC11-120; Fig. 3) (ca. 73,000 yr interpolated ^{18}O age).

6. *E. huxleyi* becomes more abundant than *G. caribbeanica* in ^{18}O Substages 5a−b in tropical and subtropical waters (V23-100, V28-239, V22-174, V28-238; Fig. 2) (ca. 85,000 yr interpolated ^{18}O age).

7. LAD *Globoquadrina pseudofoliata* occurs in ^{18}O Stage 7 in tropical waters (Thompson and Saito, 1974) (ca. 220,000 yr interpolated ^{18}O age).

8. FAD *Emiliania huxleyi* occurs in ^{18}O Stage 8 in tropical, subtropical, transitional, and subpolar waters (V23-100, V28-239, V22-174, V28-238, K708-7, V19-240, RC11-120; Figs. 4, 5) (ca. 275,000 yr interpolated ^{18}O age).

9. LAD *Stylatractus universus (= Axoprunum angelinum)* occurs near base of ^{18}O Stage 11 (at base of carbonate-dissolution stage B9) in tropical to subantarctic waters (V28-238, V28-239, V20-119, V19-28, E49-18, RC13-205, RC13-229, RC14-37; Fig. 14) (ca. 460,000 yr interpolated ^{18}O age).

10. LAD *Pseudoemiliania lacunosa* occurs in ^{18}O Stage 12 in tropical, subtropical, transitional, and subpolar waters (V23-100, V28-239, V22-174, V28-238, K708-7, E49-18; Fig. 3) (ca. 474,000 yr interpolated ^{18}O age).

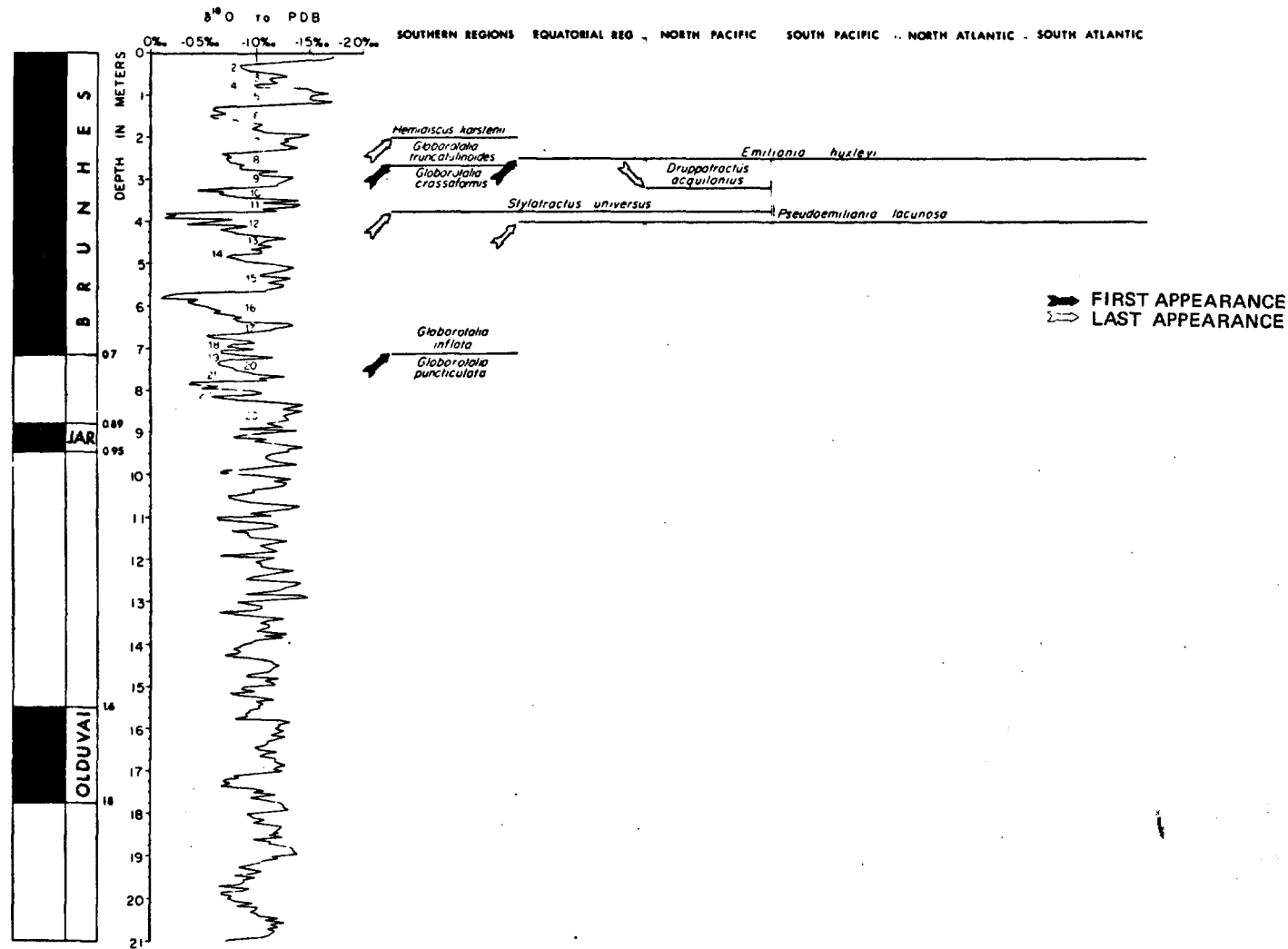11. Acme *Roperia tesselata* var. *ovata*

FIG. 16. Correlation of biostratigraphic datum levels to the oxygen-isotope stratigraphy and geomagnetic-reversal scale.
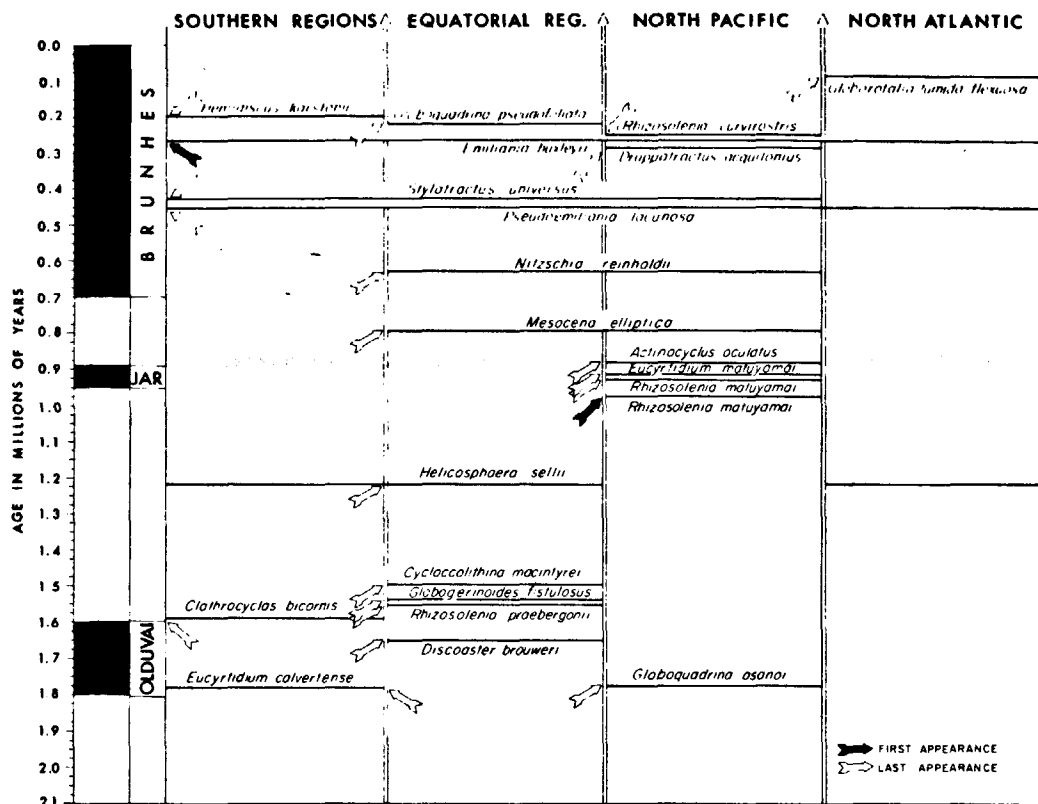
FIG. 17. Correlation of biostratigraphic datum levels to the geomagnetic-reversal scale.

occurs in carbonate-dissolution stage B17+ (= near base ^{18}0 Stage 17) in tropical waters (RC11-209; Table 2, Figs. 10, 11) (ca. 677,000 yr interpolated ^{18}0 age).

12. LAD *Nitzchia reinholdii* occurs below carbonate-dissolution stage B17 (= ^{18}0 Stage 18) in tropical and subtropical waters (RC11-209; Table 2, Figs. 10, 11) (ca. 700,000 yr interpolated ^{18}0 age).

13. Brunhes/Matuyama reversal (Mankinen and Dalrymple, 1979) (ca. 0.73 my).

14. Abundance increase in *Thalassiosira oestrupii* occurs near the base of carbonate-dissolution stage M1 (= lower part of ^{18}0 Stage 21) in tropical waters (RC11-209; Table 3, Figs. 10, 11) (ca. 776,000 yr interpolated ^{18}0 age). (The extrapolated ^{18}0 age is calculated on the basis of a sedimentation rate of 0.9 cm/1000 yr for the interval 726 to 1553 cm in V28-239, cf. rate of ca. 1.0 cm/1000 yr from 25- to 715-cm depth (Shackleton and Opdyke,

1976), and gives ^{18}0 boundaries of stages 19–20 at 700,000 yr, of 20–21 at 726,000 yr, of 21–22 at 756,000 yr, and of 22–23 at 809,000 yr).

15. LAD *Mesocena elliptica* occurs near the top of carbonate-dissolution stage M3 (= at the boundary between ^{18}0 Stages 22 and 23) in tropical waters (RC11-209; Table 2, Figs. 10, 11) (ca. 830,000 yr interpolated ^{18}0 age).

16. Top of Jaramillo event, within ^{18}0 Stage 23 (880,000 yr).

17. LAD *Eucyrtidium matuyamai* occurs in the lower part of the Jaramillo event in the North Pacific (Fig. 15) (ca. 0.9-my interpolated magnetic-reversal age).

18. LAD of dominant small *Gephyrocapsa* also occurs in the lower part of the Jaramillo event in tropical and subtropical waters (Fig. 6) (ca. 0.92-my interpolated magnetic-reversal age).

19. Bottom of Jaramillo event (on the

same basis as the extrapolated ¹⁸O ages, this boundary at 940-cm depth in V28-239 would approximate to 0.94 my).

20. FAD *Mesocena elliptica* occurs about one-eighth of the way between the bottom of the Jaramillo and the top of the Olduvai magnetic-reversal event in tropical waters (RC11-209; Figs. 10, 11) (ca. 1.0-my interpolated magnetic-reversal age).

21. LAD *Helicopontosphaera sellii* occurs midway between the bottom of the Jaramillo and the top of the Olduvai magnetic-reversal event in tropical and subtropical waters (DSDP 154A, 206, 289; see Fig. 6) (ca. 1.33-my interpolated magnetic-reversal age).

22. FAD *Asteromphalus hiltonianus* occurs about midway between the bottom of the Jaramillo and top of the Olduvai magnetic-reversal event in tropical waters (RC11-209; Figs. 10, 11) (ca. 1.28-my interpolated magnetic-reversal age).

23. LAD *Rhizosolenia praebergoni* var. occurs just above the Olduvai magnetic-reversal event in tropical waters (RC11-209; Figs. 10, 11) (ca. 1.6-my interpolated magnetic-reversal age).

24. LAD *Globigerinoides fistulosus* occurs just above the Olduvai magnetic-reversal event in tropical and subtropical waters (RC11-252, V16-205; Fig. 12) (ca. 1.6-my interpolated magnetic-reversal age).

25. LAD *Pterocanium prismatium* occurs just above the Olduvai magnetic-reversal event in tropical waters (Fig. 15) (ca. 1.6-my interpolated magnetic-reversal age).

26. LAD *Cyclococcolithina macintyrei* occurs just above the Olduvai magnetic-reversal event in tropical and subtropical waters (DSDP 154A, 206, 289; see Fig. 6) (ca. 1.0-my interpolated magnetic-reversal age).

27. FAD *Gephyrocapsa oceanica* occurs near the top of the Olduvai magnetic-reversal event in tropical and subtropical waters (DSDP 154A, 206, 289; see Fig. 6) (ca. 1.65-my interpolated magnetic-reversal age), and just above the Olduvai magnetic-reversal event in Mediterranean waters (ca.

1.74-my interpolated magnetic-reversal age; see Haq *et al.*, 1977).

28. Top of Olduvai event at 1.72 my.

29. LAD *Globigerinoides obliquus* occurs at the top of the Olduvai magnetic-reversal event in tropical and subtropical waters (RC11-252, V16-205; Fig. 12) (ca. 1.72-my interpolated magnetic-reversal age).

30. LAD *Clathrocyclus bicornis* occurs near the top of the Olduvai magnetic-reversal event in subantarctic waters (Fig. 15) (ca. 1.72-my interpolated magnetic-reversal age).

31. FAD *Gephyrocapsa caribbeanica* occurs just below the top of the Olduvai magnetic-reversal event in Mediterranean waters (Haq *et al.*, 1977) (ca. 1.74-my interpolated magnetic-reversal age but may occur above or below this level in tropical or subtropical areas (DSDP 154A, 206, 289; see Fig. 6).

32. LAD *Discoaster brouweri* occurs near the top of the Olduvai magnetic-reversal event in tropical and subtropical waters (DSDP 154A, 202, 289; see Fig. 6, Haq *et al.*, 1977) (ca. 1.77-my interpolated magnetic-reversal age).

33. LAD *Lamprocyclas heteroporos* occurs in the lower part of the Olduvai magnetic-reversal event in North Pacific waters (Fig. 15) (ca. 1.8-my interpolated magnetic-reversal age).

34. FAD *Eucyrtidium matuyamai* occurs in the lower part of the Olduvai magnetic-reversal event in North Pacific waters (Fig. 15) (ca. 1.84-my interpolated magnetic-reversal age).

35. FAD *Pseudoeunotia doliolus* occurs near the base of the Olduvai magnetic-reversal event in tropical and subtropical waters (RC11-209; Figs. 10, 11) (ca. 1.8-my interpolated magnetic-reversal age).

36. Bottom of Olduvai event at 1.8 my (occurs at 1.88 my on the basis of extrapolated ages for V28-239).

37. FAD *Globorotalia truncatulinoides* occurs just below the base of the Olduvai magnetic-reversal event in subtropical and transitional waters (RC11-252, V16-205;

Fig. 12) (ca. 1.9-my interpolated magnetic-reversal age).

38. LAD *Eucyrtidium calvertense* occurs below the base of the Olduvai magnetic-reversal event in subantarctic waters (Fig. 15) (ca. 1.9-my interpolated magnetic-reversal age).

39. LAD size increase in *Rhizosolenia praebergonii* occurs just below the base of the Olduvai magnetic-reversal event in tropical waters (Fig. 9, Table 3) (ca. 2.0-my interpolated magnetic-reversal age).

40. LAD *Globorotalia exilis* occurs just below the base of the Olduvai magnetic-reversal event in tropical waters (? RC11-252, V16-205; Fig. 12) (ca. 2.0 my interpolated magnetic-reversal age).

41. LAD *Globorotalia miocenica* occurs below the base of the Olduvai magnetic-reversal event in tropical waters (? RC11-252, V16-205; Fig. 12) (ca. 2.1-my interpolated magnetic-reversal age).

42. LAD *Thalassiosira convexa* occurs midway between the Gauss/Matuyama boundary and the base of the Olduvai magnetic-reversal event in tropical and subtropical waters (Fig. 9, Table 2) (ca. 2.2-my interpolated magnetic-reversal age).

43. FAD *Gephyrocapsa aperta* occurs below the base of the Olduvai magnetic-reversal event in Mediterranean waters (ca. 2.3-my interpolated magnetic-reversal age) (Haq *et al.*, 1977).

44, 45. LAD *Helotholus vema* and *Desmospyris spongiosa* occur at the Gauss/Matuyama magnetic-reversal boundary in subantarctic waters (Fig. 15) (ca. 2.47-my magnetic-reversal age).

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