30. NEOGENE MAGNETOBIOSTRATIGRAPHY OF DEEP SEA DRILLING PROJECT SITE 516 (RIO GRANDE RISE, SOUTH ATLANTIC)[1]

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ABSTRACT

Calcareous plankton biostratigraphy (foraminifers and nannoplankton) and magnetostratigraphy of the upper Oligocene to Pleistocene have been studied in hydraulic piston Cores 516-1 to 516-44, 516A-5 to 516A-11, and 516F-1 to 516F-11, Rio Grande Rise (water depth 1313 m). Some 80 biostratigraphic datum events have been correlated to the magnetic polarity stratigraphy over an interval representing the Matuyama to Chron 5, and Chrons 16 to 23. Coring disturbance and biostratigraphic evidence of a condensed section preclude unambiguous identification of polarity or biostratigraphic events over an approximately 30-m interval in the middle and upper Miocene. Sedimentation rates varied considerably during the Neogene, but an abnormally thick upper Oligocene and lower Miocene section allows a high degree of magnetobiochronologic resolution. A new planktonic foraminiferal zonation for the Miocene completes the midlatitude Neogene zonation of the South Atlantic.

Important magnetobiostratigraphic correlations at Site 516 and their estimated magnetochronology include: (1) Oligocene/Miocene boundary = first appearance datum (FAD) *Globorotalia kugleri* = last appearance datum (LAD) *Reticulofenestra bisecta* = mid-Anomaly 6C (Chron 23) = 23.7 Ma; (2) Aquitanian/Burdigalian boundary = LAD *G. kugleri* = between base Anomaly 6A and top of unnumbered anomaly between 6A and 6B (Chron 21) = 21.8 Ma; (3) Zone N6/N7 boundary = LAD *Catapsydrax dissimilis* (= FAD *G. pseudomiozea* and *G. zealandica*) = Chron 16/17 boundary = 17.6 Ma; (4) early/middle Miocene (= Burdigalian/Langhian) boundary = FAD *Praeorbulina sicana* = midpart of Anomaly 5C (Chron 16) = 16.6 Ma *or* FAD *P. glomerosa* = just above Anomaly 5C (inferred) = 16.3 Ma; (5) Zone N8/N9 boundary = FAD *Orbulina suturalis* above Anomaly 5C (later part Chron 16, inferred); (6) Miocene/Pliocene boundary = LAD *Globoquadrina dehiscens* = LAD *Globorotalia lenguaensis* = basal Gilbert Chron = 5.3 Ma.

INTRODUCTION

Integrated studies on planktonic biostratigraphy and magnetobiostratigraphy in deep-sea cores and on uplifted marine sections on land are providing the framework for more refined age estimates of biostratigraphic zonal boundaries, events, and chronostratigraphic boundaries. Although we now have a relatively precise magnetobiostratigraphy for the Paleogene (Alvarez et al., 1977; Lowrie et al., 1982; Poore et al., in press) and the Pliocene-Pleistocene (Hays et al., 1969; Berggren, 1973), the Miocene remains somewhat incomplete (Ryan et al., 1974), at least in terms of the calcareous plankton. The relatively complete Neogene biostratigraphy (Pujol, this volume) and magnetostratigraphy (Hamilton and Suzyumov, this volume) of Site 516 have encouraged us to make a more detailed investigation of this site.

Seven holes were drilled at Site 516 on the Rio Grande Rise in 1313 m water depth (Fig. 1). Four of these (516B to E) were abandoned with little or no recovery. The hydraulic piston corer (HPC) was used for Hole 516 to 183.3 m with 81% recovery. Hole 516A recovered the upper 69.5 m of the section with 88% recovery, and Hole 516F was washed to 169.1 m and then rotary drilled with continuous coring to 1270.6 m. Thus there is an overlap of the upper 70 m of section in Holes 516 and 516A and a 13–14 m overlap between the lower part of Hole 516 and the upper part of Hole 516F.

We have examined nearly 160 samples (105 from Hole 516, 40 from 516A, and 12 from 516F) from the upper Oligocene-Pleistocene at Site 516. An essentially complete Neogene stratigraphic succession appears to be present with a rich, well-preserved planktonic foraminiferal fauna and moderately to well-preserved calcareous nannoplankton floras in most samples. A markedly reduced rate of sedimentation (condensed section) is postulated over an interval of about 14 m (between 56 and 70 m sub-bottom = Cores 516-14 to 516-17), and an upper Miocene unconformity may lie between Core 516-14 and Section 516-13-2 at about 56 m sub-bottom. In this 14-m interval, many calcareous plankton taxa associated with middle-upper Miocene stratigraphy are present together, and distinct (bio)stratigraphic separation is not possible.

A relatively complete Neogene polarity stratigraphy has been recorded at Site 516. Elements of the Matuyama (beginning with the Jaramillo Event), Gauss, and Gilbert chrons and the latest part of Chron 5 were identified in Cores 516-1 to 516-13 above the inferred hiatus at approximately 55 to 56 m. Cores 516-14 and 516-15

[1] Barker, P. F., Carlson, R. L., Johnson, D. A., et al., *Init. Repts. DSDP*, 72: Washington (U.S. Govt. Printing Office).

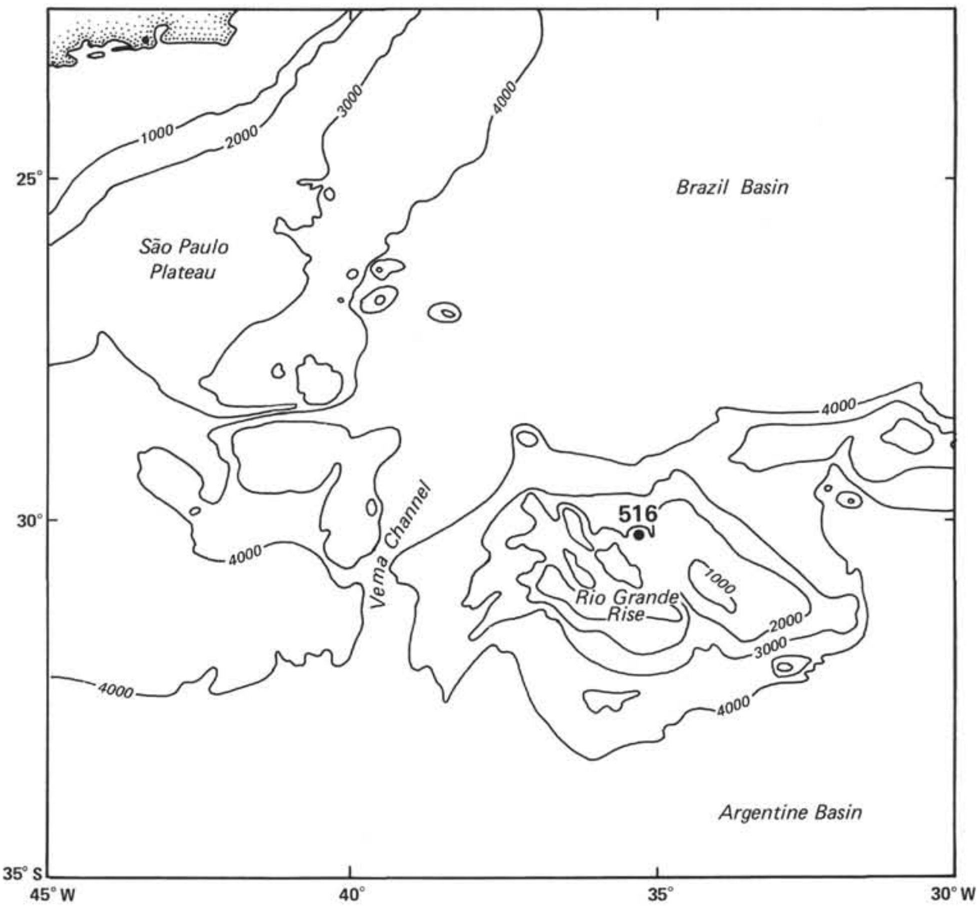


Figure 1. Location map, Site 516.

contain a normal polarity for which an unambiguous assignment is difficult. A sampling gap from 63 to 85 m, caused by considerable caving disturbance, renders this interval unsuitable for paleomagnetic study. Below this an interval, samples from Anomaly 5C (Chron 16) to the normal event above Anomaly 6B (Chron 21) were recovered. The upper part of Hole 516F overlaps the basal part of Hole 516, and elements of Chrons 21–23 are recorded in the interval covered by this report (Cores 516F-1 to 516F-11).

In this paper, we present the results of an integrated study of calcareous plankton biostratigraphy and magnetic polarity stratigraphy. We are able to identify a relatively large number of late Oligocene–Pliocene datum levels; we believe this identification has added considerably to our understanding of datum level magnetobiostratigraphy for the past 25 Ma.

MATERIALS AND METHODS

Magnetostratigraphy

The shipboard natural remanent magnetization (NRM) investigation consisted of a study of some 175 samples taken from the cores obtained from the Neogene section of Holes 516 and 516A and some 370 samples from the cores recovered from the deep penetration Hole 516F (only the Neogene of Hole 516, the Pliocene of Hole 516A, and the basal Neogene and upper Oligocene of Hole 516F [Cores 1-11] are considered in this report).

Shipboard remanence measurement was hampered by low levels of magnetization of the biogenous sediments at Site 516. Magnetic intensities close to or only barely above instrument noise levels of approximately 0.3 mA/m characterize many samples. As a result, relatively few samples were subjected to alternating field (AF) demagnetization on board ship. The majority of samples were remeasured on shore and subjected to magnetic cleaning by use of either a peak AF of 20 mT or thermal demagnetization to 280°C (for results of individual magnetic measurements, see site chapter, Site 516, this volume). The chron terminology used for magnetic units follows that of Tauxe and her colleagues (personal communication, 1982) developed in connection with investigations on DSDP Leg 73.

Biostratigraphy

Samples for our studies of planktonic foraminifers and calcareous nannoplankton were prepared according to standard procedure. In general, one sample per section was examined. Planktonic foraminifers are generally very well preserved, calcareous plankton moderately to well preserved (dissolution occurs in upper Miocene and basal Pliocene assemblages of Cores 516-12 to 516-13, and secondary calcification occurs in the condensed middle Miocene section, Cores 516-14 and 516-15, particularly). A notable feature of the cores from Hole 516 is that samples from Section 1 of each core often exhibited signs of downhole contamination (primarily Pleistocene, and less commonly Pliocene, elements). With this exception, cores from Hole 516 and 516F appear to contain *in situ* microfaunas and floras.

We have found it useful to use both the "standard" zonation of Martini (1971) and the "low-latitude" zonations of Bukry (1973) and Okada and Bukry (1980) for the Neogene stratigraphy of this site. We have found it necessary to develop a midlatitude planktonic foraminiferal zonation for the uppermost Oligocene to Miocene of this site because of the transitional nature of the fauna (see following section).

Qualitative abundances for calcareous nannoplankton taxa were made from smear slides. Planktonic foraminifers have been examined on the 149-μm screen size.

MIOCENE PLANKTONIC FORAMINIFERAL ZONATION

The Neogene tropical planktonic foraminiferal zonation of Blow (1969) has found widespread application in (predominantly) low-latitude regions. Studies conducted over the past decade, however, have shown that it is of limited utility in extratropical regions. For this reason a late Neogene, late Miocene–Pliocene zonation of the midlatitude Atlantic was created (Berggren, 1973, 1977a).

In this paper we complete the Neogene midlatitude zonation of the Atlantic. Although many of the nominate taxa of Blow's (1969) Neogene tropical zonation are present here at Site 516 (and other comparable South and North Atlantic midlatitude sites), they often occur sporadically (e.g., *Catapsydrax stainforthi*), are difficult to distinguish taxonomically from associated forms (e.g., *Globoquadrina praedehiscens*) or are absent altogether (e.g., *Globigerinatella insueta*). Thus precise zonal determination is frequently difficult. On the other hand, we have found that the *Globorotalia miozea* group, useful in middle to upper Miocene biostratigraphic zonation in midlatitudes of the Atlantic and Indo-Pacific regions, is also useful in the lower Miocene, together with other associated forms. Because most of the elements of Blow's (1969) tropical Miocene zonation are also present here, it is possible to make a relatively accurate correlation between that zonation and the one proposed here.

The Miocene zonal system employed here is described below (from older to younger). The Miocene zones have been given a numerical notation (M1, M2, etc.) for use of communication, similar to the PL notation described for Pliocene zones (Berggren, 1973, 1977a, 1977b). One late Oligocene zone is defined also but is not given a numerical notation because it is not part of a scheme that extends down into the Paleogene.

With the description of these 13 Miocene zones (and one upper Oligocene zone), a midlatitude Neogene zonation of the Atlantic is essentially complete. Twenty-one zones (13 Miocene; 6 Pliocene; 2 Pleistocene) have been recognized in the Neogene. The Pleistocene zonation of Blow (1969)—Zone N22 and N23—has been retained for the moment.

Definition of Late Oligocene to Late Miocene Planktonic Foraminiferal Zones: South Atlantic

Globigerina angulisuturalis–Globorotalia mendacis Concurrent-range Zone

Age. late Oligocene (Chattian)

Definition. The partial range of the two nominate taxa between the last appearance datum (LAD) of *Globorotalia opima* s.s. and first appearance datum (FAD) of *G. kugleri*.

Remarks. This zone corresponds to the *Globigerina angulisuturalis* (P22) Zone of Blow (1969). *Globorotalia mendacis* is added to the (modified) definition of this zone because of its general usefulness in this part of the stratigraphic record and the locally sporadic development of *Globigerina angulisuturalis.* At Hole 516F, *Globigerinoides primordius* appears (as a new element) within this zone (in Core 516F-10 at 255 m) and well below (approximately 45 m) the FAD of *Globorotalia kugleri.*

Globorotalia kugleri Total-range Zone (M1)

Age. early Miocene (Aquitanian)

Definition. The total range of the nominate taxon

Remarks. This zone corresponds to the total range of *Globorotalia kugleri.* As such, it represents a return to the original definition of this zone by Bolli (1957) and Banner and Blow (1965). Because of the erratic initial appearance of *Globigerinoides primordius* (which, in some instances may be more a function of its recognition by micropaleontologists than any actual irregularity in its initial appearance), Zone N4 as redefined by Blow (1969, p. 223) has an "elastic" base. The base of Blow's (1969) Zone N4 is defined as the FAD of *G. primordius*, which was considered to have occurred within the range of *Globorotalia kugleri.* Therefore, depending on which author's data are used, the base of Zone N4 could be located anywhere within the interval between the upper part of the range of *G. opima opima* and the FAD of *Globoquadrina dehiscens.* Inasmuch as *Globigerinoides primordius* appears to have become a common component of low-latitude and midlatitude assemblages at a level close to the FAD of *Globorotalia kugleri* (this work; Pujol, this volume; Chaproniere, 1981; Stainforth and Lamb, 1981) it would appear that the use of Zone N4 (in most instances) probably corresponds to the sense in which it is defined here. The main point is that, as it is defined now, Zone N4 (Blow, 1969) is of little use.

Globigerinoides primordius Partial-range Subzone (M1a)

Age. early Miocene (Aquitanian)

Definition. The partial range of the nominate taxon between the FAD of *Globorotalia kugleri* and the FAD of *Globoquadrina dehiscens*

Remarks. The FAD of *G. dehiscens* occurs within the range of *Globorotalia kugleri* and provides a convenient means of subdividing the *G. kugleri.* Total-range (M1) Zone into two parts characterized by the partial range of *Globigerinoides primordius* (below) and *Globoquadrina dehiscens* (above). The LAD of *Globigerina angulisuturalis* coincides with the FAD of *Globoquadrina dehiscens* in Hole 516F.

Globorotalia kugleri/Globoquadrina dehiscens Concurrent-range Subzone (M1b)

Age. early Miocene (Aquitanian)

Definition. The concurrent range of the two nominate taxa between the FAD of *Globoquadrina dehiscens* and the LAD of *Globorotalia kugleri*

Remarks. This zone corresponds to the upper part of the *Globigerinoides quadrilobatus primordius/G.* (*Turborotalia*) *kugleri* (N4) Concurrent-range Zone of Blow (1969).

Globorotalia incognita–Globorotalia semivera Partial-range Zone (M2)

Age. early Miocene (Burdigalian)

Definition. Partial range of the two nominate taxa between the LAD of *Globorotalia kugleri* (base) and the FAD of *G. praescitula* (top).

Remarks. The two nominate taxa are common in the lower Miocene of southwestern Atlantic sites and appear to have had a widespread geographic distribution (Walters, 1965; Jenkins, 1971; Berggren and Amdurer, 1974; Keller, 1981a; Srinivasan and Kennett, 1981). They are in the ancestral line to the *G. miozea* group that developed in the later part of the early Miocene.

At Site 516 (see also Site 357: Boersma, 1977), this zone corresponds essentially to the total range of a particular ecophenotype variant of *Globoquadrina* (referred to as *G. dehiscens* forma *spinosa*). The form is generally abundant and characterized by being tightly coiled; the umbilical region is covered by a "bulla", and the test is covered by a dense spinose "coating" . The *Globorotalia incognita–G. semivera* Partial-range Zone corresponds essentially to Zones N5 and N6 of Blow (1969); its upper limit virtually coincides with the LAD of *Catapsydrax dissimilis* (= top of Zone N6).

Globorotalia zealandica–Globorotalia pseudomiozea
Total-range Zone (M3)

Age. early Miocene (Burdigalian)

Definition. The total range of the two nominate taxa, *Globorotalia zealandica* and *G. pseudomiozea*

Remarks. We have observed the evolutionary development of these two taxa from, and coincident with the disappearance of, *G. incognita* and *G. semivera* at Site 516 at a level that virtually coincides with the N6/N7 boundary of Blow (1969). The two nominate taxa have a short and virtually identical stratigraphic range (see also Walters, 1965, p. 116), which appears to be restricted to within Zone N7. It may be that *G. zealandica* is an inflational, encrusted ecophenotypic variant of *G. pseudomiozea*, but the two taxa are retained as separate entities pending our quantitative studies on the evolution of this group.

The FAD of *G. praescitula* occurs at the base of this zone in our samples, and this taxon appears to be related to, if not descended from, *G. zealandica.*

Globorotalia miozea **Partial-range Zone (M4)**

Age. early Miocene (Burdigalian)

Definition. The partial range of the nominate taxon between its FAD and that of *Praeorbulina sicana*

Remarks. We have observed that the FAD of *G. miozea* occurs at virtually the same level as the LADs of *G. zealandica* and *G. pseudomiozea* and somewhat earlier than the FAD of *P. sicana.*

Praeorbulina sicana–Globorotalia miozea
Partial-range Zone (M5)

Age. middle Miocene (Langhian)

Definition. The partial range of the nominate taxa between the FAD of *Praeorbulina sicana* and that of *P. glomerosa*

Remarks. Our observations indicate that the LAD of *P. sicana* coincides with the FAD of *Orbulina suturalis.* However, Blow (1969, p. 229) indicates that *P. sicana* extends into Zone N9. We have chosen to limit the extent of the *P. sicana* Zone to the partial range before the FAD of *P. glomerosa*, so that this event may be used in midlatitude biostratigraphy and provide a link with a well-recognized biostratigraphic horizon in low latitudes. As such, this zone (M5) is not equivalent to the *Globigerinoides sicanus* (N8) zone of Blow (1969).

This zone is characterized by the common occurrence of *Globorotalia miozea, G. praescitula*, and *G. peripheroronda*, the latter of which appears for the first time in its typical form within this zone.

Praeorbulina sicana–Praeorbulina glomerosa
Partial-range Zone (M5)

Age. middle Miocene (Langhian)

Definition. The range of the nominate taxa between the FAD of *Praeorbulina glomerosa* and that of *Orbulina* (*O. suturalis*)

Remarks. The FAD of *P. glomerosa* provides a distinct and useful means of recognizing a stratigraphic interval just before the appearance of *Orbulina.* We have observed that the FAD of *P. glomerosa* coincides essentially with that of the minute and minutely biapertured form *Globigerinoides diminutus* at Site 516. *Globorotalia miozea, G. praescitula*, and *G. peripheroronda* are particularly common and characteristic of this interval.

Orbulina suturalis–Globorotalia peripheroronda
Concurrent-range Zone (M7)

Age. middle Miocene (Langhian-Serravallian)

Definition. The concurrent range of the two nominate taxa between the FAD of *Orbulina suturalis* and the LAD of *Globorotalia peripheroronda*

Remarks. This zone differs from the *O. suturalis–G.* (*Turborotalia*) *peripheroronda* (N9) Partial-range Zone of Blow (1969) in that its upper limit is defined here by the disappearance of *G. peripheroronda*, not by the partial (i.e., concurrent) range of the two nominate taxa before the first evolutionary appearance of *G.* (*T.*) *peripheroacuta*, nominate taxon of Zone P10. Inasmuch as *G. peripheroacuta* and, indeed, other succeeding keeled members of the *G. fohsi* lineage are very rare in this area of the South Atlantic, the use of the upper (post-*Orbulina*) part of the range of *G. peripheroronda* until its extinction is considered a more useful means of biostratigraphic zonation at these latitudes. As such, this zone corresponds approximately to Zones N9 and N10 of Blow (1969, p. 232).

Globigerina druryi **Partial-range Zone (M8)**

Age. middle Miocene (Serravallian)

Definition. The partial range of the nominate taxon between the LAD of *Globorotalia peripheroronda* and the FAD of *Globigerina nepenthes*

Remarks. This zone corresponds approximately to the interval of Zones N11 to N13 of Blow (1969).

Globigerina nepenthes **Consecutive-range Zone (M9)**

Age. middle Miocene (Serravallian)

Definition. The range of the nominate taxon from its evolutionary first appearance from *Globigerina druryi* to the FAD of *Globorotalia paralenguaensis*

Remarks. This zone corresponds very closely to Zone N14 of Blow (1969).

Globorotalia paralenguaensis–Neogloboquadrina continuosa **Partial-range Zone (M10)**

Age. middle to late Miocene (Serravallian-Tortonian)

Definition. The partial range of the two nominate taxa between the FADs of *Globorotalia paralenguaensis* and *Neogloboquadrina acostaensis*

Remarks. This zone corresponds very closely to Zone N15 of Blow (1969).

Globorotalia miozea–Globorotalia conoidea **Partial-range Zone (M11; here amended)**

Age. late Miocene (Tortonian)

Definition. The partial range of the two nominate taxa between the FAD of *Neogloboquadrina acostaensis* and *Globorotalia conomiozea/G. mediterranea*

Remarks. The original definition of this zone, as a concurrent range zone of the two nominate taxa, requires correction inasmuch as both of the nominate taxa occur below the level of the criterion (FAD *N. acostaensis*) suggested for defining its base. The ranges of these taxa, as thus defined, do not meet the requirement of a concurrent-range zone.

Globorotalia conomiozea–Globorotalia mediterranea **Partial-range Zone (M12; here amended)**

Age. late Miocene (early and middle Messinian)

Definition. The partial range of the nominate taxa between their virtually simultaneous FADs and the FAD of *Globorotalia cibaoensis–margaritae* s.l.

Remarks. This zone was originally defined (Berggren, 1977a) as a concurrent-range zone. The fact that these two taxa appear virtually simultaneously and that the top of the Zone was originally defined by the FAD of another taxon, *G. margaritae*, indicates that this zone should be considered a partial-range zone, rather than a concurrent-range zone. The upper limit, as here modified, is drawn at the level at which forms referable to the nonkeeled *G. cibaoensis* ($\stackrel{?}{=}$ *G. margaritae primitiva*) occur. Taxonomic studies are being conducted on this group to resolve the relationships among its various members.

Globorotalia margaritae s.l.–*Globoquadrina dehiscens* **Concurrent-range Zone (M13)**

Age. latest Miocene (late Messinian)

Definition. The concurrent range of the two nominate taxa between the FAD of *Globorotalia margaritae* s.l. and the LAD of *Globoquadrina dehiscens* (Berggren, 1977a, b)

Remarks. The order of the names of this zone have been reversed here to reflect the fact that *Globorotalia margaritae* has its FAD within this zone, whereas *Globoquadrina dehiscens* has its LAD within the zone (Blow, 1969, p. 222).

NEOGENE BIOSTRATIGRAPHY OF SITE 516

Late Oligocene to Pleistocene biostratigraphy of the calcareous plankton of Site 516 is shown in Figures 2 to 6. Biostratigraphic zonation and datum level stratigraphy are summarized in Figures 7 to 11.

Planktonic Foraminifers

This section deals with the stratigraphic distribution of the more stratigraphically useful taxa of planktonic foraminifers at Site 516 for the purpose of correlation of various biostratigraphic datum events to the observed magnetic polarity record (see Pujol, this volume, for a more comprehensive assessment of the planktonic foraminiferal faunas). With few exceptions, the stratigraphic range of most taxa recorded here is similar to that recorded by Pujol (this volume).

Cores 516-1 to 516-44 span the Pleistocene to lower Miocene; Hole 516 terminated within the range of *Globorotalia kugleri.* (Hole 516A was not examined for planktonic foraminifers.) Cores 1 and 2 (upper half) of the rotary-drilled Hole 516F overlap Cores 40 to 44 of HPC Hole 516. Cores 516F-1 to 516F-11 were examined in connection with this study; Core 516F-11 is within the upper Oligocene (Zone P22 of Blow, 1969).

Upper Oligocene through Lower Miocene

The stratigraphy of Site 516 will be discussed in stratigraphic order (older to younger). Cores 1 to 11 in Hole 516F span the upper Oligocene to lower Miocene (169–274 m sub-bottom depth). Small globigerinids of the *Globigerina praebulloides-occlusa* group and round globoquadrinids of the *globularis–praedehiscens* group dominate upper Oligocene faunas. Stratigraphically important accessory taxa include *Globigerina angulisuturalis, G. euapertura, Globigerinoides primordius* (extremely rare), *Globorotalia mendacis, G. pseudokugleri, Globoquadrina venezuelana*, and *Catapsydrax dissimilis.*

The FAD of *Globigerinoides primordius* occurs in 516F-10-1, 100 cm (255 m), well below that of *Globorotalia kugleri* (516F-5-1, 110 cm; 208 m) and above the LAD of "*Globorotalia*" *opima* s.s. (Cores 516F-14/516F-15; approximately 300 m sub-bottom depth; Pujol, this volume) in contradistinction to the suspicion voiced by some (including W.A.B.) that these taxa overlap in the upper Oligocene.

The upper Oligocene/lower Miocene transition is characterized by a relatively rapid taxonomic turnover in the form of FADs and LADs in the *Globorotalia kugleri–pseudokugleri–mendacis* group, FAD of *Globoquadrina dehiscens* and LAD of *Globigerina angulisuturalis*, and the diversification of the genus *Globigerinoides.*

Lower Miocene fauna are dominated by globigerinids of the *woodi–brazieri* group, globoquadrinids of the *dehiscens–baroemoenensis–praedehiscens* group, and small globorotaliids of the *semivera–incognita* group. *Catapsydrax dissimilis, Globorotaloides suteri*, and *Globigerinoides* of the *trilobus–altiaperturus* and *subquadratus* groups occur in frequencies fluctuating from rare to abundant.

An occurrence of interest is that of a spinose variant of *Globoquadrina dehiscens.* This form appears abruptly and essentially coincident with the LAD of *Globorotalia kugleri* and ranges through approximately 50 m of lower Miocene sediments (to mid-Core 516-30). It was observed previously by Boersma (1977) and appears to span the major part of the interval of Zones N5 and N6 of Blow (1969).

The upper part of the lower Miocene is characterized by the sequential appearance of members of the *Globorotalia miozea* group (FAD of *G. zealandica–pseudo-*

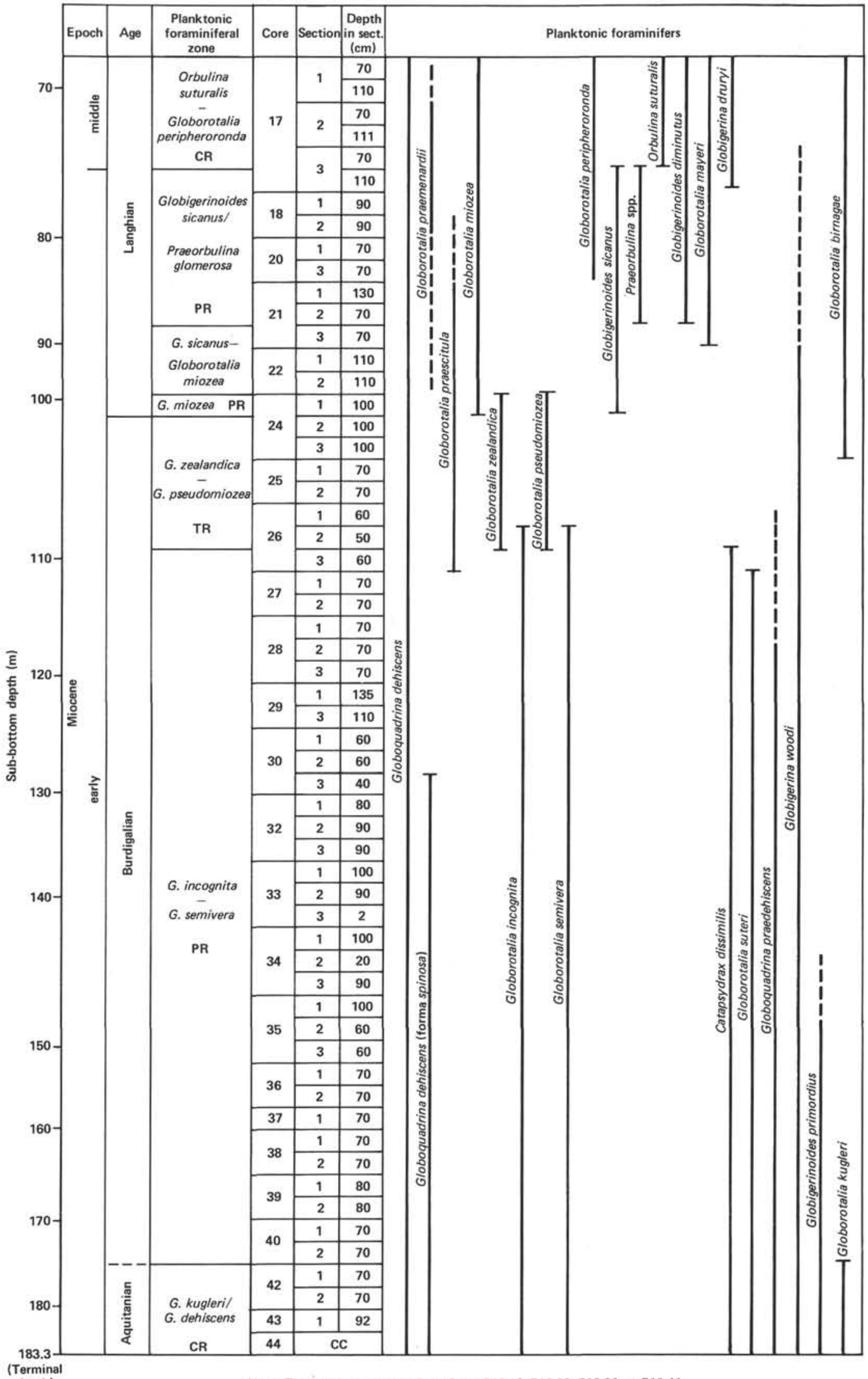


Figure 2. Stratigraphic distribution of selected planktonic foraminifers in Hole 516: early to middle Miocene. CR = Concurrent-range zone, PR = Partial-range zone, TR = Total-range zone.

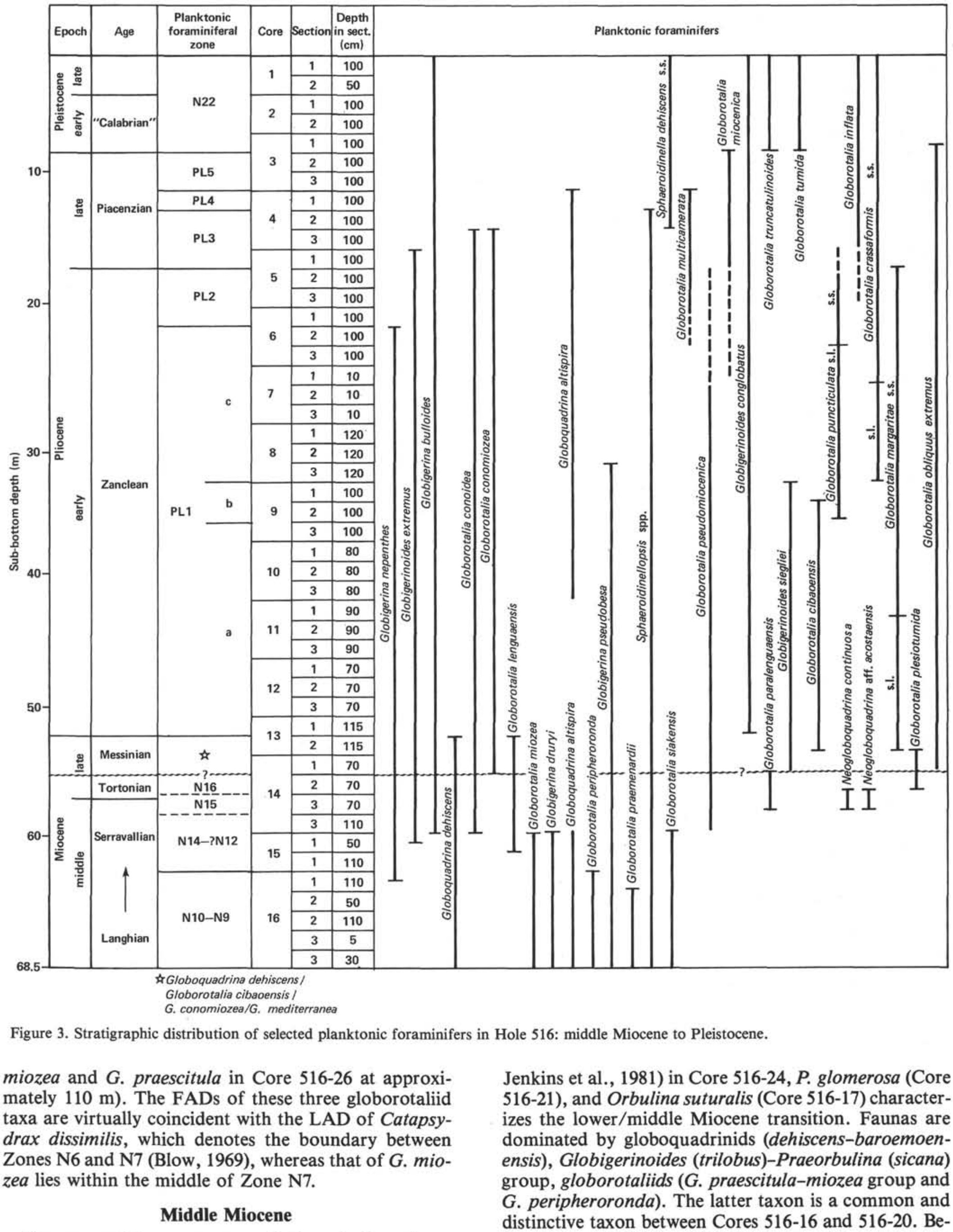


Figure 3. Stratigraphic distribution of selected planktonic foraminifers in Hole 516: middle Miocene to Pleistocene.

miozea and *G. praescitula* in Core 516-26 at approximately 110 m). The FADs of these three globorotaliid taxa are virtually coincident with the LAD of *Catapsydrax dissimilis*, which denotes the boundary between Zones N6 and N7 (Blow, 1969), whereas that of *G. miozea* lies within the middle of Zone N7.

Middle Miocene

The sequential appearance of *Praeorbulina sicana* (we follow the taxonomic revision of this group made by Jenkins et al., 1981) in Core 516-24, *P. glomerosa* (Core 516-21), and *Orbulina suturalis* (Core 516-17) characterizes the lower/middle Miocene transition. Faunas are dominated by globoquadrinids (*dehiscens-baroemoenensis*), *Globigerinoides* (*trilobus*)-*Praeorbulina* (*sicana*) group, *globorotaliids* (*G. praescitula-miozea* group and *G. peripheroronda*). The latter taxon is a common and distinctive taxon between Cores 516-16 and 516-20. Between Cores 516-17 and 516-20 it serves to characterize pre-*Orbulina* levels together with the praeorbulinids and

G. miozea; between Cores 516-16 and 516-17 it is a useful guide, together with *Orbulina suturalis*, to the Zone N9–11 (equivalent) interval in the absence of the subsequent members of *G. fohsi* lineage.

The interval between Cores 516-12 and 516-14 is extremely difficult to interpret. The LAD of *G. peripheroronda* (516-16-2, 50 cm; 66 m sub-bottom) is interpreted as indicative of a level equivalent to Zone N11 (Blow, 1969). In the succeeding 10 m (Cores 516-14 to 516-16), there is evidence of a very condensed sequence of the middle to late Miocene, as seen in the concurrent presence of various taxa normally separated in time: *Globigerina nepenthes, Globorotalia paralenguaensis, G. merotumida, G. plesiotumida, Neogloboquadrina continuosa, N. acostaensis.* The disappearance of *G. siakensis, G. miozea*, and *Globigerina druryi* near the top of Core 516-15 and the presence of *G. nepenthes* suggests an interval correlative with Zones N14 to N16 (the earlier occurrence of *G. nepenthes* overlapping with *Globorotalia peripheroronda* as low as 516-16-1, 110 cm may be caused by downhole contamination).

Upper Miocene and Pliocene

A typical upper Miocene fauna, including *Globorotalia conoidea, G. conomiozea, Globoquadrina dehiscens, Globigerinoides siegliei, Sphaeroidinellopsis* spp., and *Globigerina pseudobesa*, occurs at 516-14-1, 70 cm (approximately 56 m sub-bottom). This fauna is similar to that recorded at Site 357 (357-5-4, 100 cm) above a suggested unconformity between Zones N14 and N17 (Berggren, 1977b). The concurrence of various taxa normally present over the interval N13 to N16 suggests that this interval is probably present in Hole 516 but in a strongly condensed sequence. A possible hiatus may occur within Core 516-14 (approximately 56–57 m sub-bottom) between and within Zones N16 to N17.

The LADs of *Globoquadrina dehiscens* and *Globorotalia lenguaensis* and the FAD of the *G. cibaoensis–margaritae* s.l. group (516-13-2, 115 cm; approximately 53 m sub-bottom) is used to denote the Miocene/Pliocene boundary (Berggren, 1973; 1977a, b).

The Pliocene spans the interval between 516-3-2 and 516-13-2, 115 cm (approximately 53 to 9 m sub-bottom). Pliocene faunas are rich and diverse, and both the composition and biostratigraphic sequence are fully comparable to previous reports from this area (Berggren, 1977a, b). Faunas are characterized by components of the *G. conomiozea* group, the *G. cibaoensis–puncticulata–crassaformis–inflata* group, and the *Sphaeroidinellopsis–Sphaeroidinella* group. The FAD of *G. truncatulinoides* occurs in Core 516-3 (about 9 m), and the Pliocene/Pleistocene boundary is placed at a level just above this datum level.

Pleistocene faunas (Cores 1 and 2 of Hole 516) were not studied in detail. Ranges of a few taxa are taken from Pujol (this volume).

Calcareous Nannoplankton

Calcareous nannofossils were examined for biostratigraphic zonation and correlation of the main datum events to the observed magnetic polarity record over the stratigraphic interval that spans the upper Oligocene–Pleistocene (see Figs. 4 to 6). The relationship between biostratigraphic events and magnetostratigraphy is shown in Figures 7 to 10.

Calcareous nannofossils provide a relatively good biostratigraphic control except for the Miocene-lowest Pliocene interval (between Sections 516-11-3 and 516-14-3; approximately 45–57 m sub-bottom), where strong dissolution results in considerably impoverished assemblages and sporadic stratigraphic occurrences of some taxa. Upper Oligocene through lower Miocene as well as middle through upper Pliocene assemblages are rich and moderately well preserved. In the upper middle Miocene (Cores 516-15 and 516-16 and the lower part of Core 516-14), where a condensed section appears to be present, preservation is poor because of overgrowth. An unconformity may occur between Cores 516-13 and 516-14.

The stratigraphy of Site 516 (Holes 516 and 516F) will be discussed in stratigraphic order (older to younger).

Upper Oligocene through Lower Miocene

Cores 516F-1 to 516F-11 (169–274 m sub-bottom) span the upper Oligocene to lowest Miocene. Upper Oligocene assemblages in the lower part of the hole (Cores 516F-9 to 516F-11) are assigned to Zone NP25 based on rare occurrences of *Sphenolithus ciperoensis.* Lower Miocene nannofloras, assigned to the *Discoaster druggi* (NN2) Zone, are present in Cores 516F-1 to 516F-3 based on the FAD of *D. druggi* in Core 516F-3. Age determination of the intervening interval (Cores 516F-4 to 516F-8) is controversial and depends upon the criteria used to recognize the Oligocene/Miocene boundary. Various interpretations use the NP25/NN1 boundary as defined by the LAD of *S. ciperoensis, Reticulofenestra bisecta, Zygrhablithus bijugatus*, and *Helicosphaera recta* (Martini, 1971, 1976; Müller, 1976) or the top of the *R. abisecta* Subzone (Bukry, 1973), which is denoted by the end of the acme of this taxon. At this site, the successive disappearance of these various taxa occur over the interval of Cores 516F-4 to 516F-8, and an anomalous co-occurrence of *H. recta* and *D. druggi* occurs in Cores 516F-1 to 516F-3 and in Cores 516-39 to 516-44.

The Oligocene/Miocene boundary is drawn here at the last occurrence of *R. bisecta*, at about 208 m, sub-bottom, within Section 516F-5-1. Upper Oligocene floras are dominated by *R. abisecta, R. gartneri, R. bisecta, Cyclococcolithus floridanus*, and *Z. bijugatus.*

Lower Miocene assemblages are present in Cores 516F-1 to 516F-4 and Cores 516-22 through 516-44 and are characterized by abundant *C. floridanus*, discoasters of the *D. deflandrei* group, *Sphenolithus* spp., and *Helicosphaera* spp. (see Table 6 later in this paper). Large numbers of *R. bisecta* and *Z. bijugatus* are sporadically found up to Core 516-37 and are considered to be reworked. *H. recta* was found in all samples up to Core 516-39. Rare occurrences of *H. ampliaperta* and the presence of *Triquetrorhabdulus carinatus* above the last occurrence of *S. belemnos* prevented the use of Martini's (1971) zonation for the lower Miocene interval. Bukry's (1973) zonation was found to be more suitable. The *D. druggi* Subzone is recognized in Cores 516F-1 to 516F-3 and from Section 516-29-2 to Core 516-44; the *S. belemnos* Zone corresponds to the range of the index species from the top of Core 516-26 to Section 516-29-1. As mentioned above, *H. ampliaperta* could not be used with accuracy to recognize the base of the *S. heteromorphus* Zone, which extends up to Core 516-17.

Middle Miocene

The stratigraphy of the interval between 516-4-2, 70 cm (56 m sub-bottom) and 516-17-2, 70 cm (70.7 m sub-bottom) was difficult to establish because of poor preservation and lack or rarity of the markers. Nannofossils are of low diversity, strongly overgrown (discoasters) or etched (coccoliths), and often broken, as a result of low sedimentation rate. Above the LAD of *Sphenolithus heteromorphus* in Sample 516-17-2, 111 cm (71.1 m sub-bottom), no datum level could be reasonably recognized. *Discoaster kugleri* was not found; however, the presence of *D. challengeri* in Sample 516-16-1, 50 cm, suggests a probable assignment of the interval from Core 516-16 through Sample 516-17-2, 50 cm (64.1–70.5 m sub-bottom) to Zones NN6 and NN7, undifferentiated. The samples examined from Core 516-15 were highly contaminated. *Catinaster coalitus* was frequent in Sample 516-14-3, 110 cm, indicating Zone NN8. A few *D. hamatus* were found in Sample 516-14-3, 70 cm, along with *C. coalitus*, characteristic of the lower part of NN9.

Upper Miocene and Pliocene

Intensive dissolution has impoverished the calcareous nannofossil assemblages between Sections 516-11-2 and 516-14-2. As a result, poorly preserved index species are masked by abundant solution-resistant nannofossils. *Discoaster berggrenii* and *D. asymmetricus* are scarce and broken. Representatives of the genus *Amaurolithus* are very rare.

Sections 516-14-1 and 516-14-2 yield abundant *D. bellus* and are assigned to Zone NN10.

Discoaster surculus, D. berggrenii, A. delicatus, D. asymmettricus were first found in Sample 516-13-2, 110 cm, and *A. primus* and *Scyphosphaera globulata* in Sample 516-13-1, 110 cm. Typical *D. quinqueramus* were not found. These simultaneous first occurrences suggest an unconformity between Cores 516-13 and 516-14.

Rich assemblages occur above Sample 516-11-3, 90 cm. Nannofossils are well to moderately preserved although alternatively overgrown or dissolved. *Amaurolithus* spp. are frequent from Sample 516-11-2, 90 cm to their last occurrence in Sample 516-6-1, 100 cm. *Ceratolithus acutus* was first found in Sample 516-10-2, 80 cm, although one possible representative of the species was found in Sample 516-11-2, 90 cm. Several authors suggest that the FAD of *C. acutus* indicates the Miocene/Pliocene boundary (but see discussion below). *Ceratolithus rugosus* first occurs in Sample 516-9-2, 100 cm. The lower/upper Pliocene boundary is drawn between Sections 516-5-2 and 516-5-3, where *Reticulofenestra pseudoumbilica* becomes extinct. All the samples examined from the upper Pliocene interval are assigned to the *D. surculus* Zone (NN16).

NEOGENE MAGNETOBIOSTRATIGRAPHY

A Cautionary Note

The development of the hydraulic piston corer (HPC) holds great promise for extending the direct correlation of microfossil biostratigraphy (and particularly of biostratigraphic datum events) and paleomagnetic stratigraphy. In this way we may expect the establishment of the relationships of zonal boundaries and datum levels to polarity chrons and anomalies and, ultimately, a refinement in age determinations (estimates) for these biostratigraphic events, i.e., a true "magnetobiochronology." Current efforts of several DSDP legs are being devoted to these problems (Legs 72–74 in the South Atlantic, for instance), and we may expect rapid progress in this area in the near future.

In a series of recent papers, Keller (1980a, b; 1981a, b) has attempted to make a calibration of early, middle, and late Miocene planktonic foraminiferal datum levels of the equatorial and subtropical Pacific Ocean by cross-correlation with biosiliceous datum levels (radiolarians), which have been previously correlated elsewhere in equatorial Pacific cores to the paleomagnetic scale (Theyer et al., 1978).

An introductory comparison of some of the interrelations made by Keller (1980a, b; 1981a, b) with our own observations (Table 1) is offered to encourage caution in the acceptance of datum level biostratigraphy and biochronology as a panacea for a classic biostratigraphy that is already overburdened with taxonomic-nomenclatorial and legalistic problems.

The most apparent irregularity that one observes in comparing the two sets of observations is the convergence of a number of "datum levels" (from the FAD of *Globoquadrina dehiscens* to the LAD of *Catapsydrax stainforthi*) in DSDP Holes 77B and 296 over a relatively brief interval (less than 1 Ma) correlated with Polarity Chron 20 by Keller (1980a, table 2, p. 374; fig. 1, p. 376), which we have observed at Site 516 spread out over an interval of some 4.5 Ma between latest Polarity Chron 22 and earliest Polarity Chron 16. Keller (1980a, p. 379) has recognized that this convergence of "events" represents a stratigraphic hiatus in Hole 77B, but we would then object to this use of FAD or LAD for the appearance or interruption in stratigraphic distribution of taxa. The terms FAD and LAD in biostratigraphy should be restricted to the initial and terminal occurrences of taxa in a normal, continuous stratigraphic succession. Further differences in our respective data are no doubt caused by differing taxonomic concepts, particularly within the early members of the *Globorotalia miozea* group (Keller, 1981a), and *G. birnagae* (which we find, along with Blow, 1969, making its initial appearance in Zone N8, near the FAD of *Praeorbulina sicana*). We note further the FAD of *Globigerinoides subquadratus* in Hole 77B in Zone N8, Polarity Chron 16 (Keller, 1980a, table 2, pp. 374, 384) subsequently shifted to

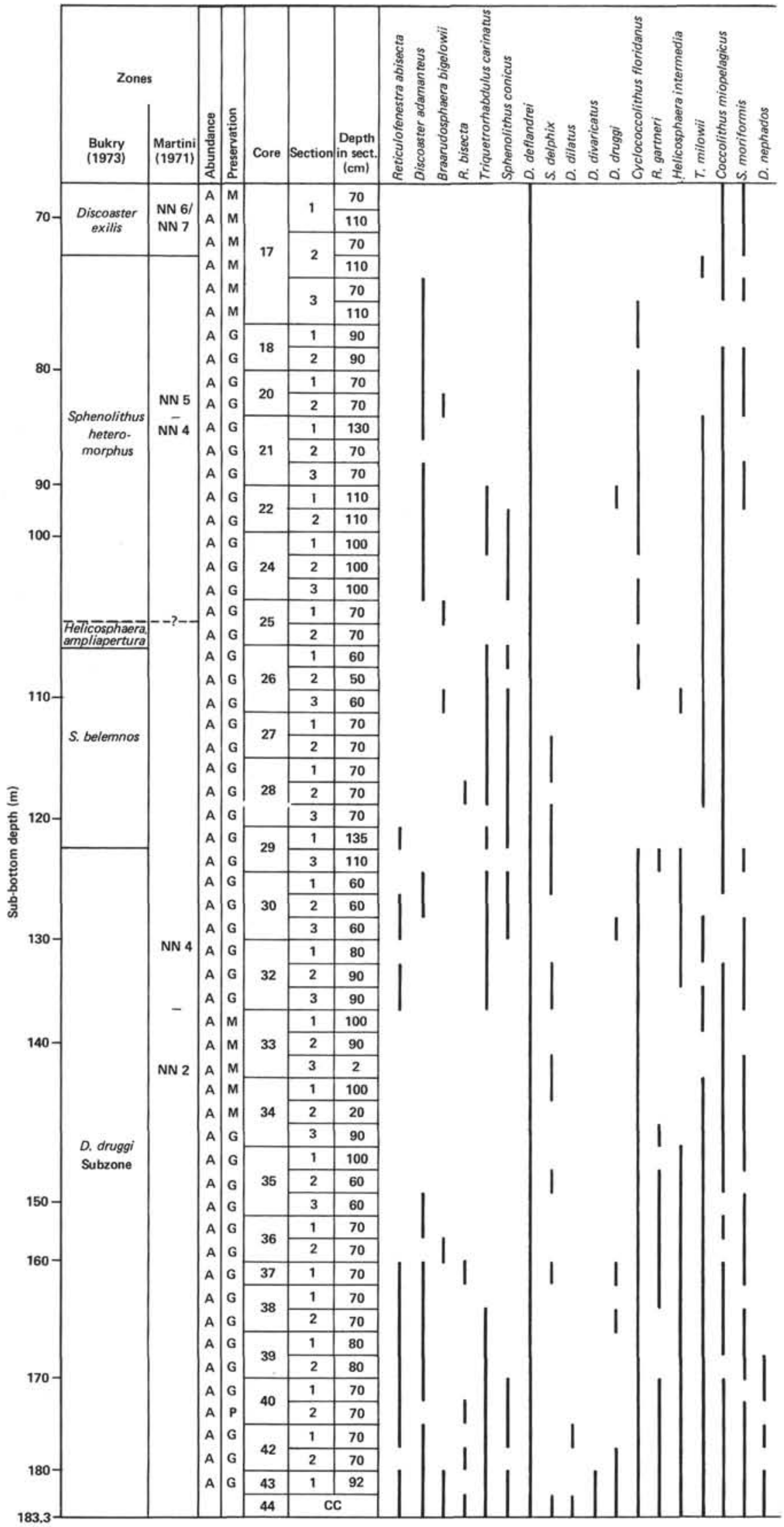


Figure 4. Stratigraphic distribution of selected calcareous nannoplankton in Hole 516: early to middle Miocene. A = abundant, C = common, M = medium, G = good, P = poor.

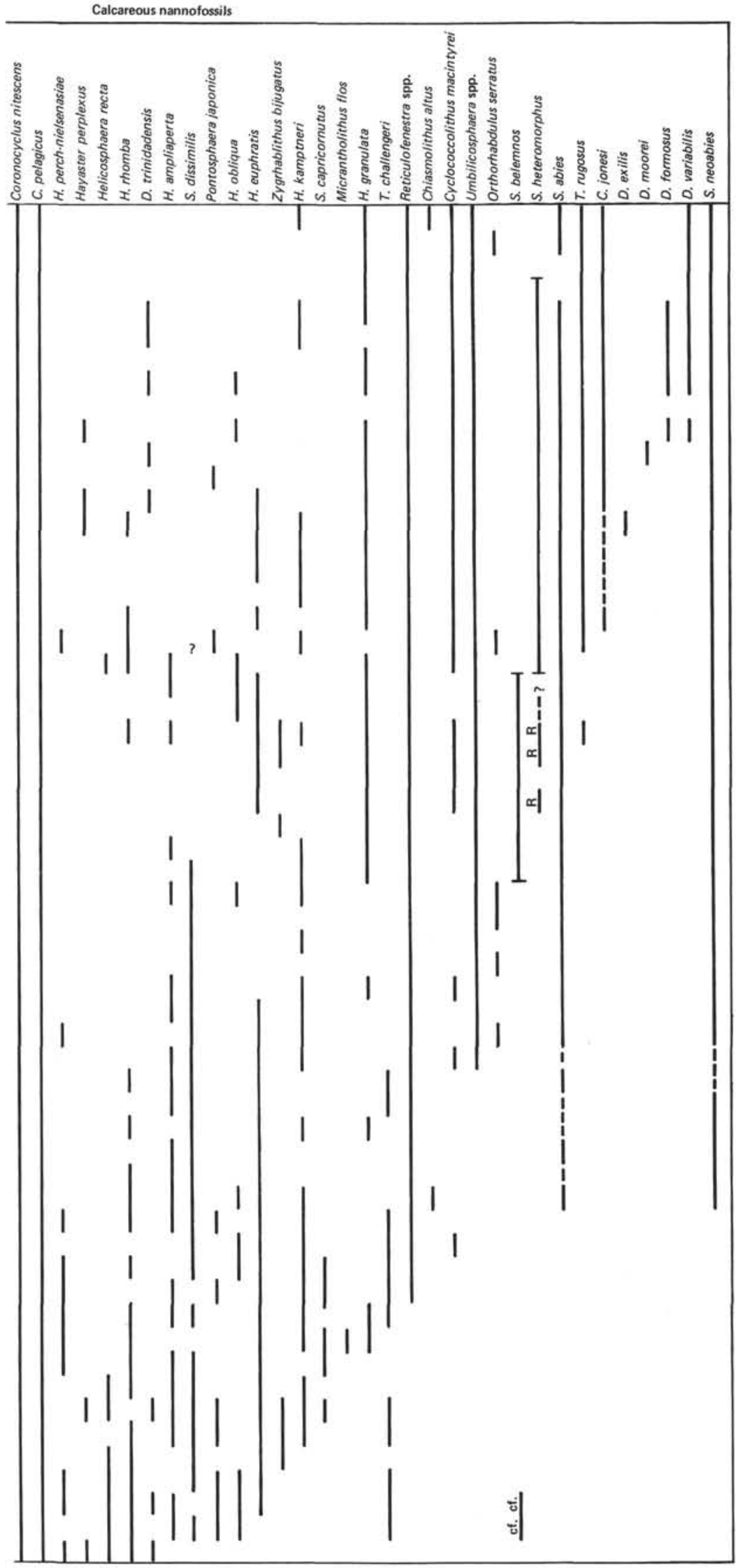


Figure 4. (Continued.)

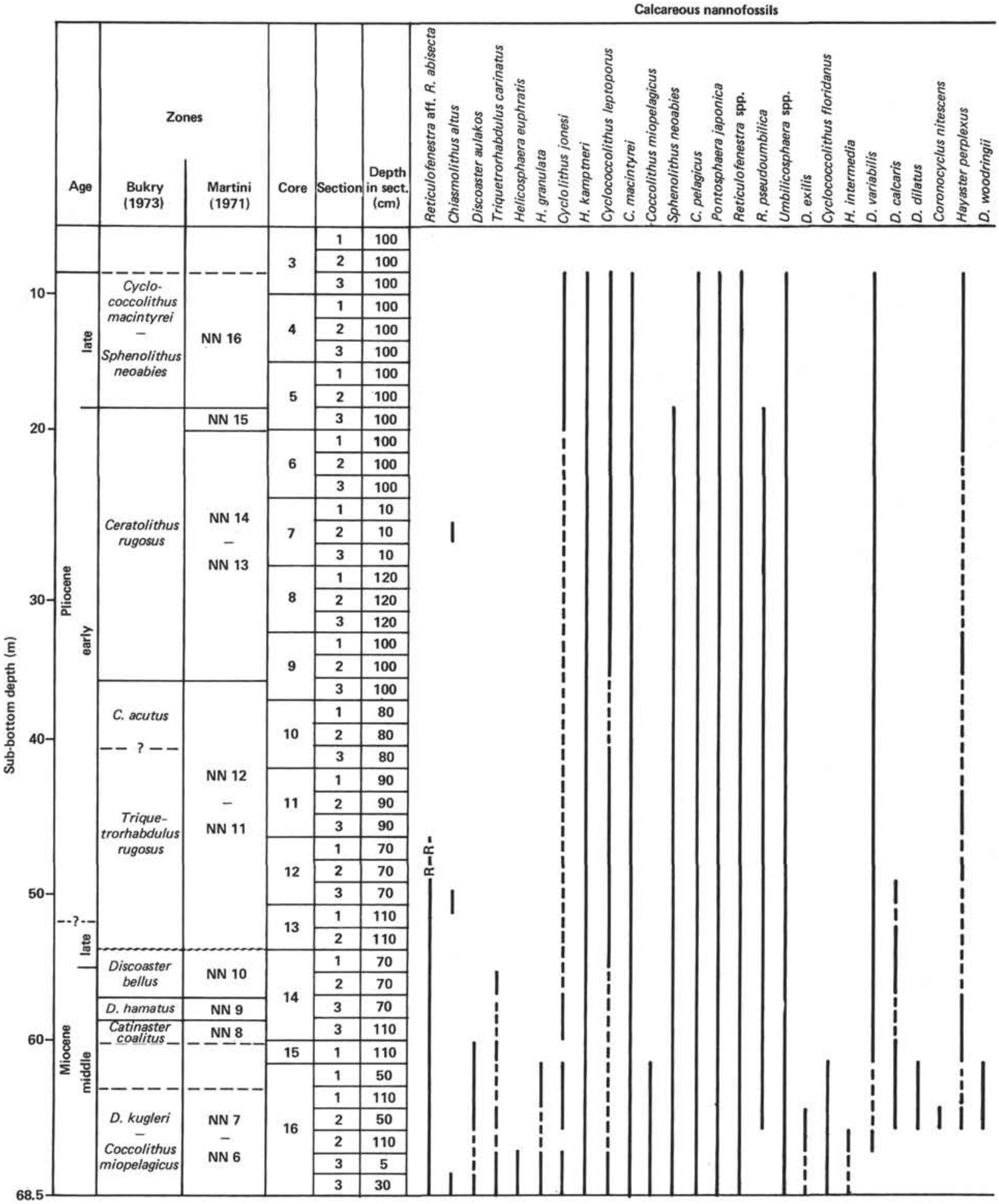


Figure 5. Stratigraphic distribution of selected calcareous nannoplankton in Hole 516: middle Miocene to Pleistocene.

mid-Zone N4 (Keller, 1981a, pp. 120, 122), coincident with the FAD of *Globoquadrina dehiscens* in Sites 71 and 292. Moreover the FAD of *Globorotalia peripheroronda* was placed (Keller, 1980a, p. 384) near the base of Zone N8 in DSDP Holes 77B and 296, as well as in Holes 55, 71, and 292, just above the FAD of *Globigerinoides* (vel *Praeorbulina*) *sicanus*, whereas this taxon was subsequently shown (Keller, 1981a, p. 125, fig. 3) developing from *Globorotalia kugleri* as low as in Zone N4. Finally, with reference to the estimated age of 22.7 Ma for the FAD of *G. kugleri* based on sedimentation rate at Site 292 (Keller, 1981a, p. 121), we would take exception to the subsequent statement that this "agrees well with the radiometric age observed by Ryan and oth-

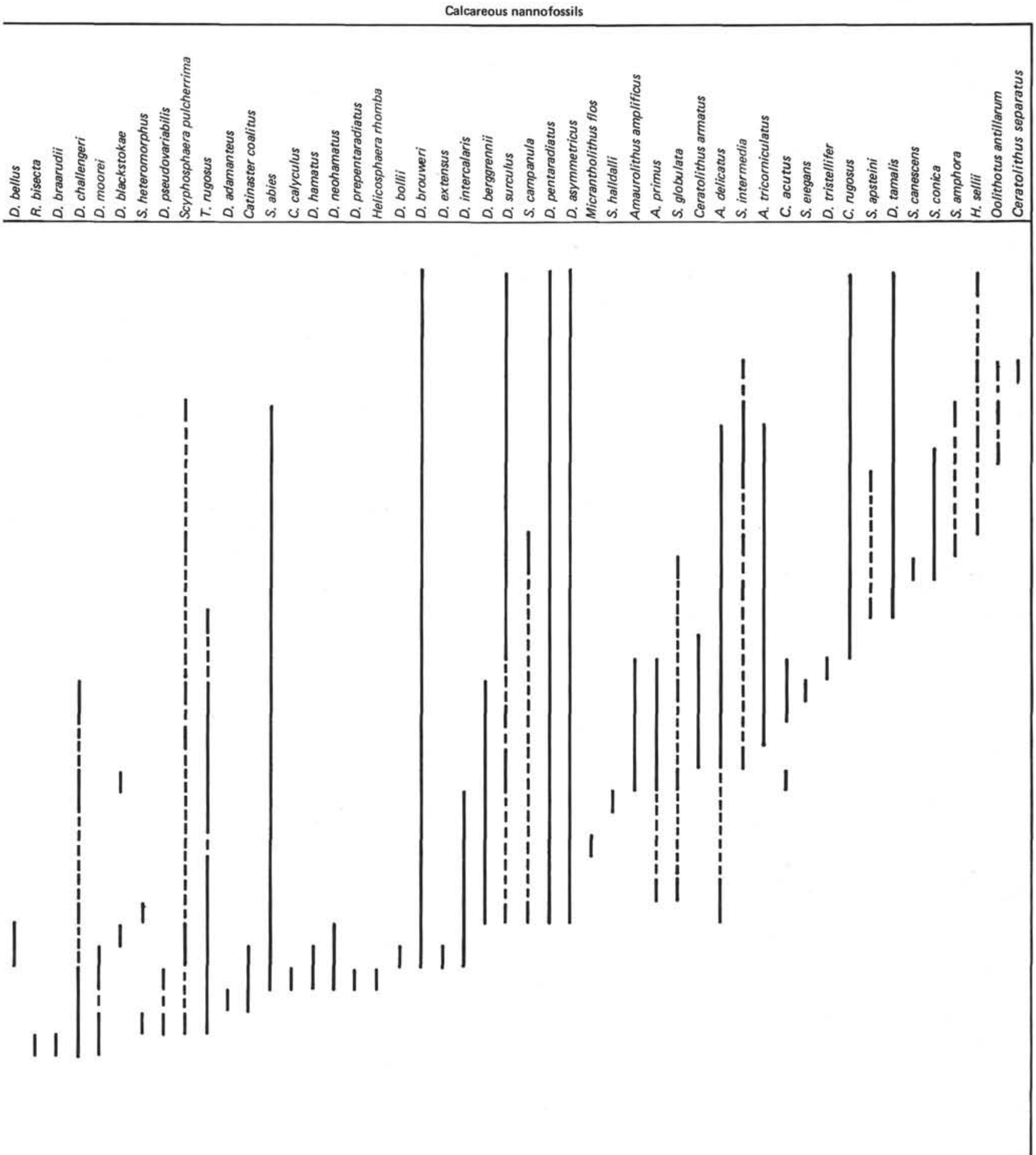


Figure 5. (Continued.)

ers (1974)" (Keller, 1981a, p. 121). First, Ryan and others (1974) neither observed, measured, nor referred to a radiometric "age" coincident with this datum (nor are we aware of such a published measurement). Secondly, radiometric determinations should more properly be referred to as "dates;" estimates of chronology based on nongeochemical methods should be referred to as "ages." The "age estimates" of Ryan and others (1974), like those by Berggren (1972) and Berggren and Van Couvering (1974), were based on extrapolations using linear sea-floor spreading rates in the one case, sedimentation rates in the other, which have been found to be consistent with published radiometric dates that span the late Oligocene/early Miocene boundary as biostratigraph-

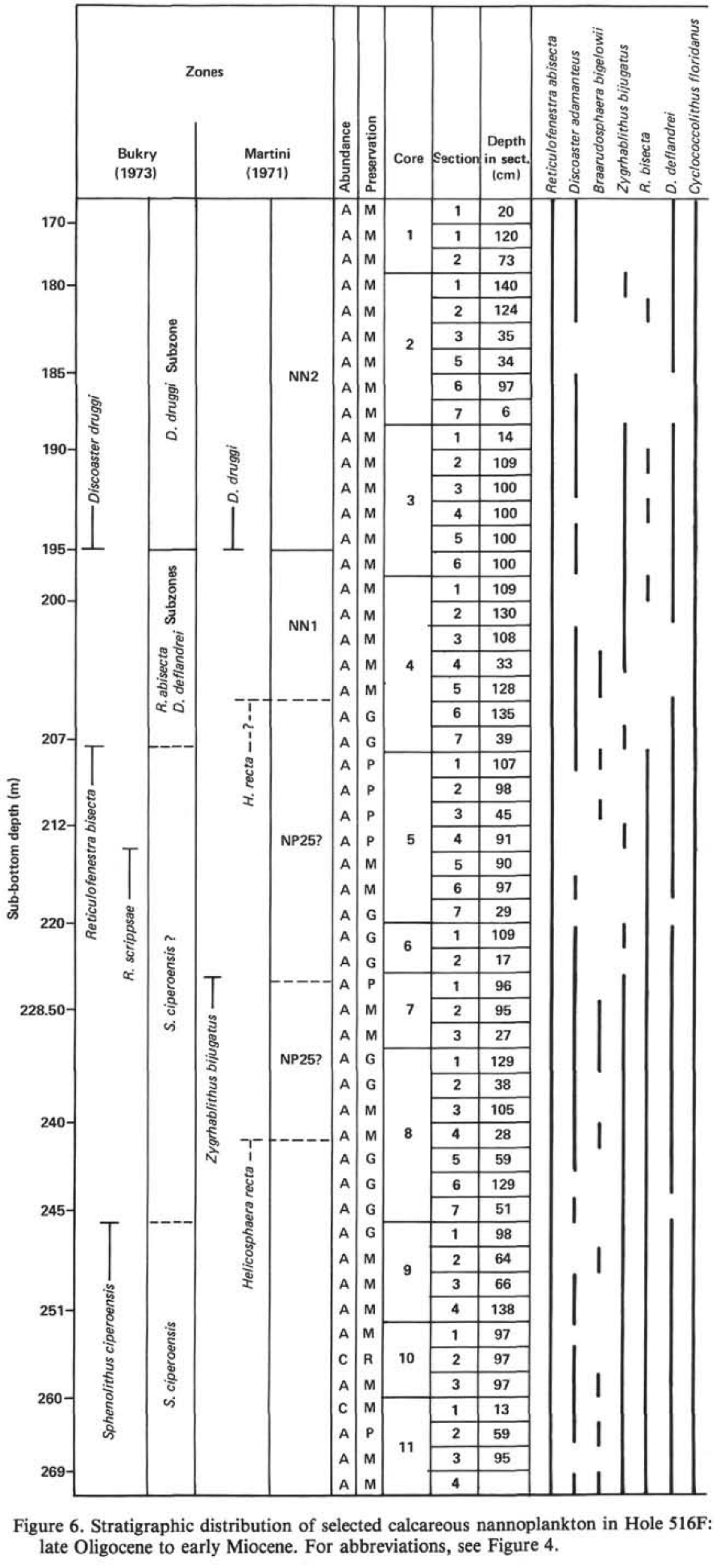


Figure 6. Stratigraphic distribution of selected calcareous nannoplankton in Hole 516F: late Oligocene to early Miocene. For abbreviations, see Figure 4.

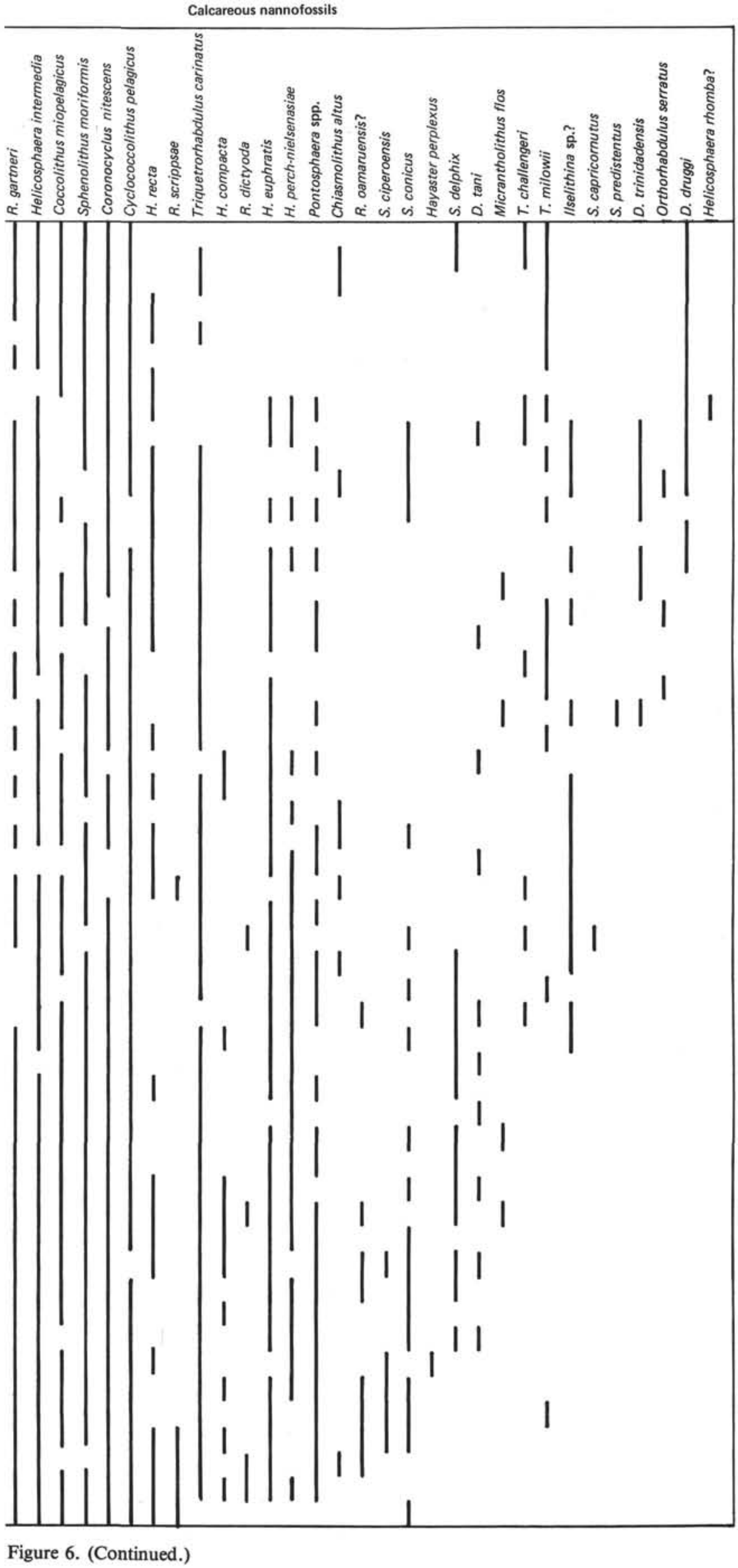
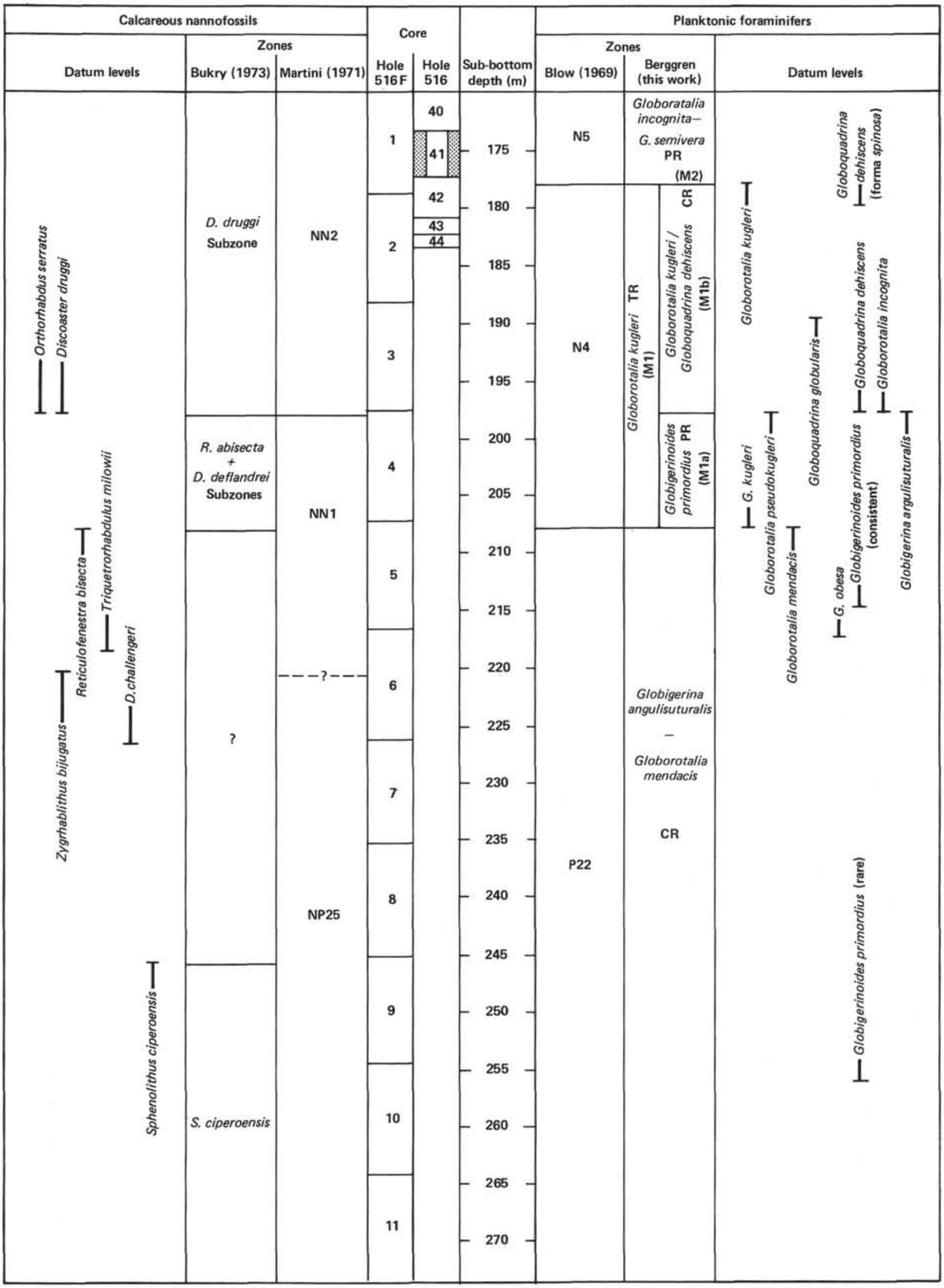
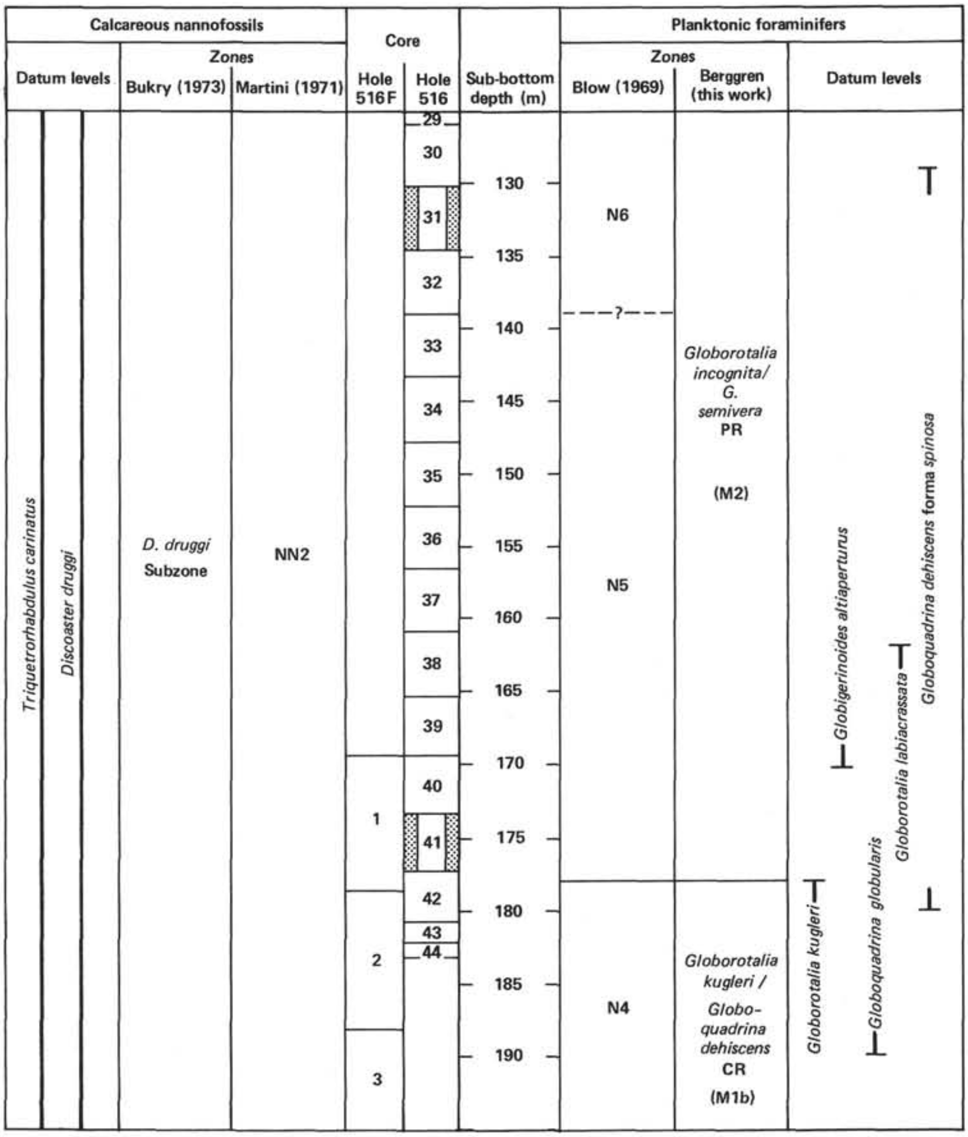


Figure 6. (Continued.)



Note: There was no recovery from Core 516-41.

Figure 7. Late Oligocene-earliest Miocene calcareous planktonic biostratigraphic datum levels in Holes 516 and 516F. For abbreviations, see Figure 2.



Note: There was no recovery from Cores 516-31 or 516-41.

Figure 8. Early Miocene calcareous planktonic biostratigraphic datum levels in Holes 516 and 516F. For abbreviations, see Figure 2.

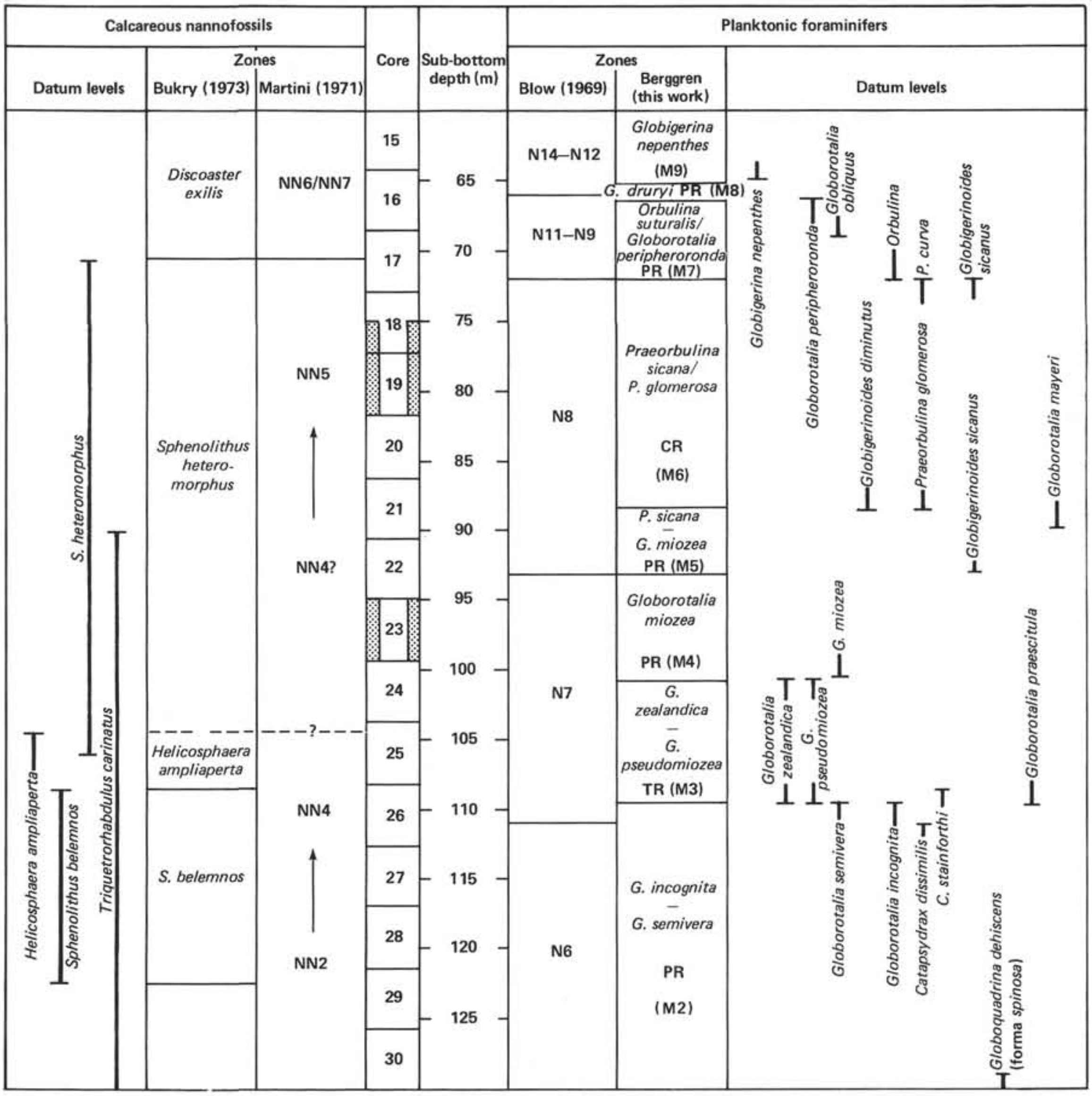
ically determined. In fact, we would interpret an "age estimate" of 22.7 Ma for the FAD of *G. kugleri* as unusually young in view of the published dates that would suggest that this level should be closer to 24 Ma (Berggren, 1981). In summary, we would urge caution on the proliferation of datum events and their indiscriminate use in biochronology. We are in danger of losing control over a very promising tool in regional biochronologic correlation.

With this caveat, we are now ready to embark upon our own journey into the uncharted waters of Neogene magnetobiostratigraphy and magnetobiochronology.

Site 516

We have identified about 80 biostratigraphic datum events (FADs and LADs) in the calcareous plankton of the latest Oligocene and Neogene (pre-Pleistocene) of Site 516 on the Rio Grande Rise (Tables 2-3). Of these, 6 are recognized in the latest Oligocene (2 planktonic foraminifers, hereinafter abbreviated as PF; 4 calcareous nannoplankton, hereinafter abbreviated to CN); 30 in the early Miocene (22 PF, 8 CN); 9 in the middle Miocene (7 PF, 2 CN); 10 in the late Miocene (5 PF, 5 CN); 27 in the Pliocene (18 PF, 9 CN). These data are tabulated in Tables 4-7. The relationships of various calcareous planktonic datum events to the observed magnetic polarity in Holes 516 and 516F, are shown in Figures 12-13, and illustrations of some of the planktonic foraminiferal (datum) taxa are in Figures 14-17.

The stratigraphic condensation over the interval between approximately 55 and 66 m sub-bottom precludes identification of datum events in the middle Miocene and early late Miocene. Our determination of datum events is conservative; we have restricted ourselves to those taxa that are relatively common (in most instances), distinct taxonomically, and/or useful biostratigraphi-



Note: No recovery in lower part of Core 18, Cores 19 and 23.

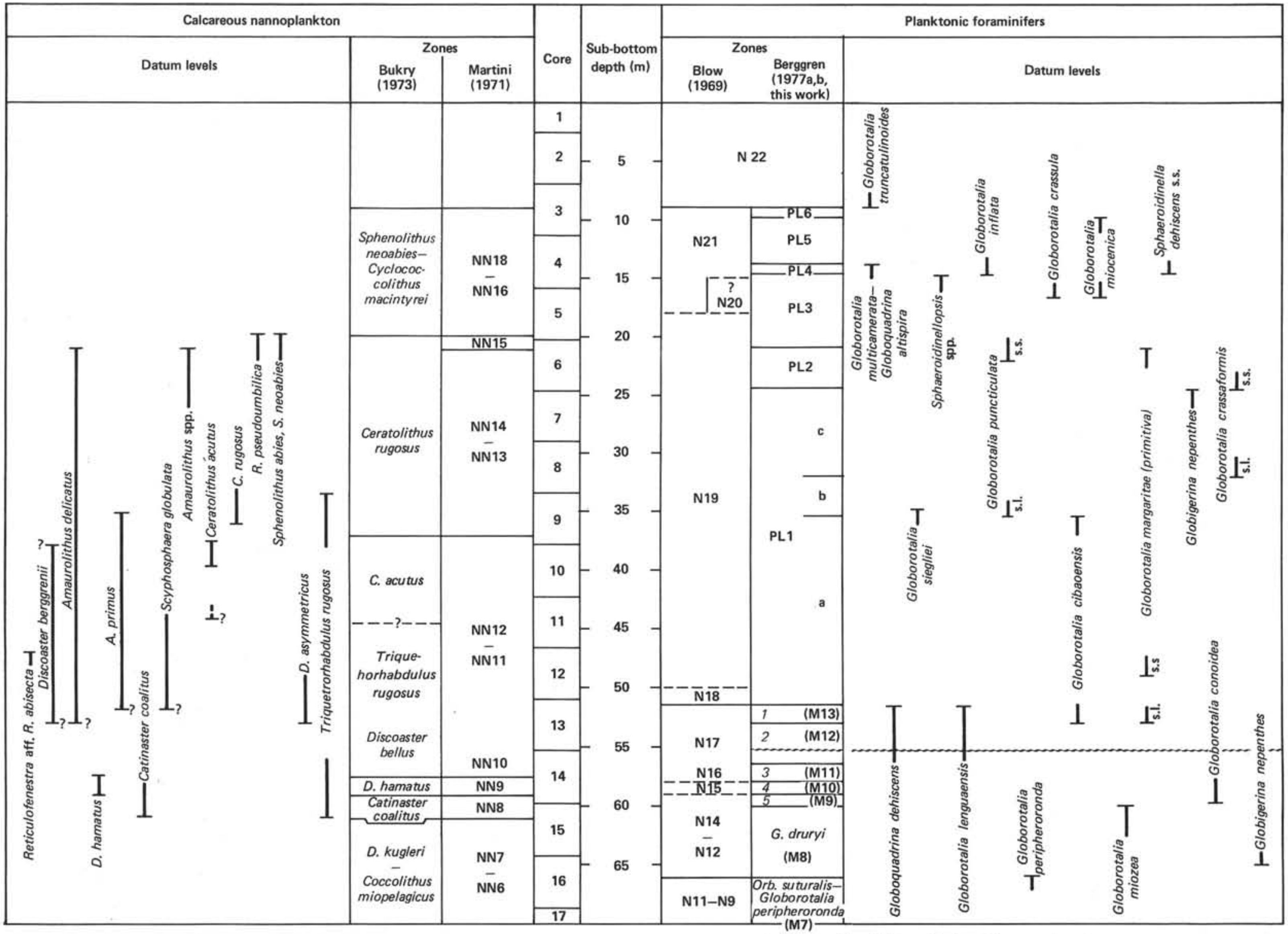
Figure 9. Early to middle Miocene calcareous planktonic biostratigraphic datum levels in Hole 516. For abbreviations, see Figure 2.

cally. Ultimately the accuracy and reliability of these datum events will depend upon two main factors: (1) correct and consistent taxonomic identification of the taxa; (2) correct identification of the polarity chron and/ or anomaly. The chronology of these datum events will depend, in turn, upon the biostratigraphically controlled, radiometrically dated horizons used as calibration points for the development of a paleomagnetic "time scale." In this study we have adopted the chronology of a recently formulated Cenozoic time scale (Berggren and Van Couvering, in press).

For the purpose of this study, the LAD of *Reticulofenestra bisecta* is taken as the definitive biostratigraphic criterion in recognizing the Oligocene/Miocene boundary (a more detailed discussion of the biostratigraphic basis for the recognition of the Oligocene/Miocene boundary is presented in Berggren and Van Couvering (in press). This datum level coincides with the FAD of *Globorotalia kugleri* in Hole 516F and is associated with Anomaly 6C (Chron 23). Attention is drawn to the FAD of *Globigerinoides primordius* in Anomaly 7 and the LAD of *Sphenolithus ciperoensis* (nominate taxon of Zone NP25) between Anomalies 6C and 7 (Fig. 12).

The LAD of *Globigerina angulisuturalis* and FAD of *Globoquadrina dehiscens* occur between Anomalies 6B and 6C simultaneously with the FADs of *Orthorhabdus serratus* and *Discoaster druggi* (nominate taxon of Zone NN2). The LAD of *Globorotalia kugleri* occurs in Chron 21, a short distance below Anomaly 6A.

There are few datum events in the interval represented by Chrons 17–21 (Table 2). The biostratigraphic range of a spinose variant of *Globoquadrina dehiscens* spans the interval between mid-Chron 21 and the lower part of Anomaly 5D in Chron 17 (Figs. 12, 15–16). The range



1 Globoquadrina dehiscens/Globorotalia margaritae s. l.
2 G. conomizea
G. mediterranea
3 G. miozea– G. conoidea
4 G. paralenguaensis– Neogloboquadrina continuosa
5 Globigerina nepenthes

Figure 10. Middle Miocene to Pleistocene calcareous planktonic biostratigraphic datum levels in Hole 516.

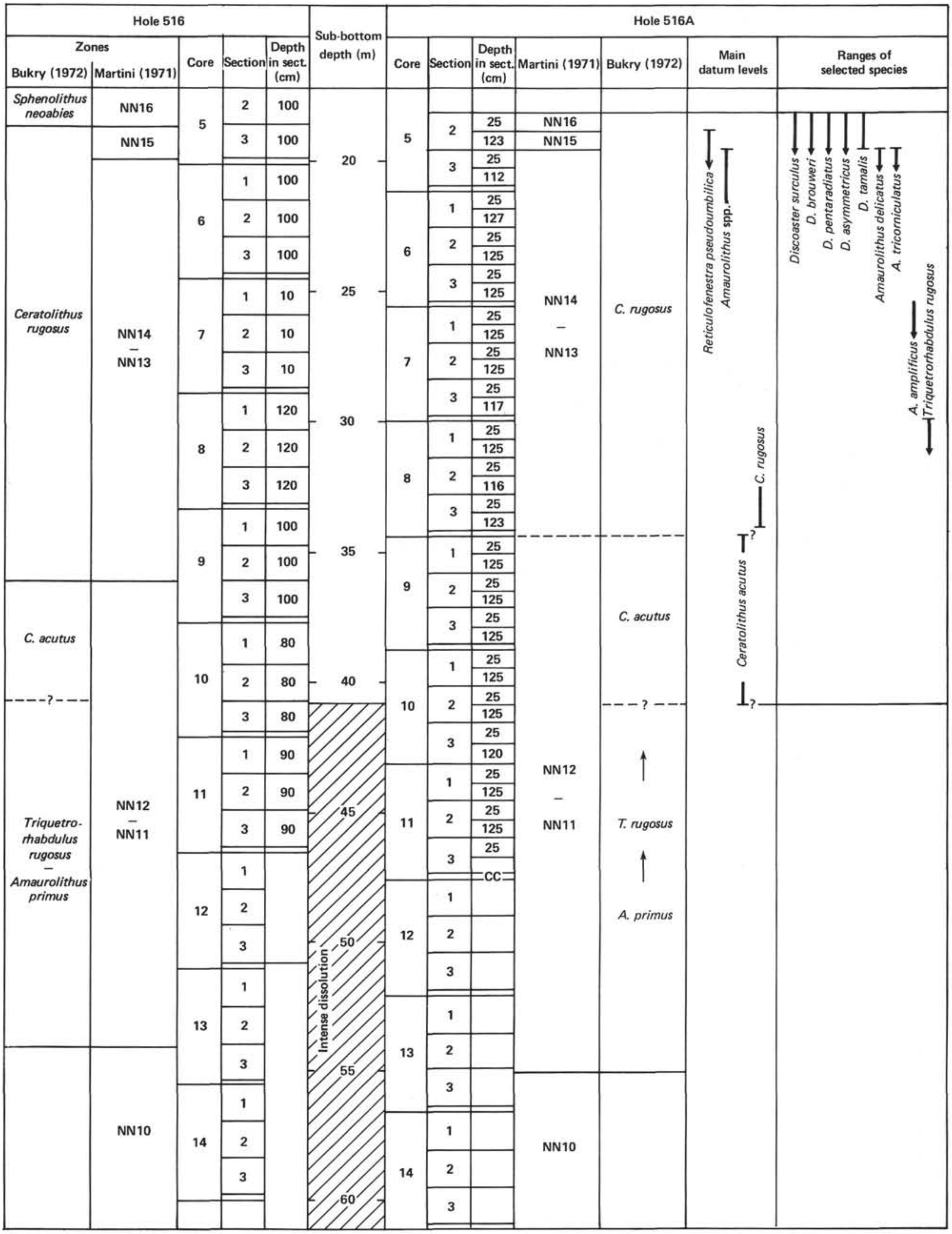


Figure 11. Comparison of Pliocene calcareous nannoplanktonic biostratigraphy at Holes 516 and 516A.

Table 1. A comparison of estimated (by secondary correlation) and directly observed magnetobiostratigraphic positions of some Neogene planktonic foraminiferal datum events.

	Estimated			Observed at Site 516	
Datum event	Hole	Zone	Chron	Chron	Zone
1. *Globorotalia peripheroronda* FAD	77B, 296	N8	16	16	N8
2a. *Globigerinoides subquadratus* FAD (1980a)	77B	N8	16	21	N4
2b. *G. subquadratus* FAD (1981b)	77B	N4	21	—	—
3. *G. diminutus* FAD	77B	N8	16	16	N8
4. *Catapsydrax stainforthi* LAD	77B	N7	20	16	N7
5. *C. dissimilis* and *C. unicavus* (LAD)	77B	N6	20	16	N7
	296	*Helicosphaera ampliaperta* (CN) *Calocycletta virginis* (R)		—	—
6. *Globorotalia zealandica* FAD	296	N6 *belemnos/ampliaperta* (CN) boundary	20	16	N7
7. *G. pseudomiozea* FAD	296	N6 *Sphenolithus belemnos* (CN)	20	16	N7
8. *G. praescitula* FAD	296	N6 *S. belemnos* (CN)	20	17	N6
9. *G. miozea* FAD	296	N6 *S. belemnos* (CN)	20	16	N7
10. *Globoquadrina kugleri* FAD	77B	N4	20	22	"N4"
	296	N4 *Coccolithus abisectus* (CN) *Lychnocanoma elongata* (R)	22		
11. *Globorotalia kugleri* FAD	77B	N4	22	32	"N4"
	292	N4 *Discoaster deflandrei* (CN)	22		
	296	N4 *Dictyococcites abisectus* (CN)	21 or 22		
12. *G. kugleri* LAD	77B	N4/5 *Discoaster druggi* (CN) *Calocycletta virginis* (R)	20	21	N4/5

Note: Estimated positions are from Keller (1980a, b; 1981a, b); direct observations are from Berggren and others (this work); FAD = first appearance datum; LAD = last appearance datum; CN = calcareous nannofossil; R = radiolarian; dashes indicate that the datum level was not assigned.

of *S. belemnos* (nominate taxon of Zone NN3) spans the later half of Chron 17 (= Anomaly 5D) and has its LAD in the early part of Chron 16.

A flurry of datum events occur beginning with Chron 16 (see Figs. 12, 17, Table 2). The LAD of *Catapsydrax dissimilis* (one of the nominate taxa of Zone N6) occurs in the earliest part of Chron 16 and is closely associated with the FADs of *Globorotalia praescitula* and the *G. zealandica-pseudomiozea* group.

The FAD of *G. miozea* occurs in the early part of Anomaly 5C correlative, whereas the FADs of *Praeorbulina sicana* (nominate taxon of Zone N8) and *P. glomerosa* occur successively in rapid order in the later part of Anomaly 5C correlative (Figs. 12, 17). The FAD of *Orbulina suturalis* occurs simultaneously with the LAD of *S. heteromorphus* (at about 71 m sub-bottom) in an interval of no paleomagnetic data above Anomaly 5C correlative. Elsewhere, the FAD of *O. suturalis* has been shown to occur as low as Anomaly 5B correlative (Poore et al., in press) and to probably lie between Anomalies 5B and 5C (Ryan et al., 1974).

In the interval between about 55 and 66 m sub-bottom, reliable biostratigraphic datum events are not discerned because of a very condensed stratigraphic section and a possible hiatus at about 55 to 56 m.

Some 36 datum events (22 PF, 14 CN) are recognized in the interval of the latest Miocene–Pliocene of Hole 516 (Table 3, Fig. 13). These datum events are essentially similar to those recognized previously by other workers, with the notable anomalous exceptions discussed below.

Discoaster asymmetricus, *D. berggrenii*, and *Amaurolithus delicatus* appear abruptly together in Section 516-13-2, and *A. primus* in Section 516-13-1 (Figs. 5, 10) associated with a normal polarity event at 53 m sub-bottom depth that may represent the Gilbert/Chron 5 boundary. An apparent unconformity occurs between Cores 516-13 and 516-14 and, unfortunately, there is about a 1.5-m interval between samples studied here (Sections 516-13-2 and 516-14-1). The taxa *primus* and *delicatus* are essentially absent up to the middle to upper part of Core 516-11, where they reappear and, together with *A. tricorniculatus* (FAD: Section 516-11-1), range into upper levels in the lower Pliocene, where their LADs are concordant with magnetobiostratigraphic correlations made previously. A rare, isolated occurrence of *Ceratolithus acutus* is noted in Section 516-11-2, but this taxon does not occur consistently until Section 516-10-2.

Haq and Berggren (1978) recognized the FADs of *primus*, *delicatus*, *tricorniculatus*, and *acutus* over a short (50 cm) interval, which essentially bracketed the Miocene/Pliocene as determined by the LAD of *Globoquadrina dehiscens* (Berggren, 1973; 1977a, b) in five piston cores (CH 64, 67, 75, 84, and 86) on the Rio Grande Rise. By calibration with previous magnetobiostratigraphic correlations, this interval appears to straddle the Gilbert/Chron 5 boundary. Ellis and Lohmann (1979) have also recorded the initial appearance of *A. primus* and *A. tricorniculatus* in basal Pliocene sediments in the Mediterranean (DSDP Site 376) and together with *A. delicatus* in the basal Pliocene of the Zanclean stratotype of Capo Rosello (Sicily), a short distance below the FAD of *C. acutus*. However, other correlations suggest that the FADs of *A. delicatus* and *A. primus* are associated with Chron 6, about 6.5 Ma (Mazzei et al., 1979; Haq et al., 1980). The FAD of *A. tricorniculatus* has been recorded in Event B of Chron 5 at about 6.0 Ma (Haq et al., 1980) and Event A of Chron 5 at about 5.5 Ma (Mazzei et al., 1979). The discrepancies noted here may be more apparent than real *if* there is an unconformity between Cores 13 and 14 in Hole 516. Alternatively, the discrepancies may represent the taxonomic "state of the art" in determining the FADs of these taxa. The sporadic occurrences of these taxa in the lower Pliocene are attributed to dissolution, which is marked in the uppermost Miocene–lowest Pliocene of the Rio Grande Rise.

A cautionary note is sounded at this point with regard to the inclusion of these "datum events" here. It is not possible to determine, from the data, whether these are indeed true FADs or subsequent appearances above a postulated unconformity. The importance in the context of this report is that these forms appear (i.e., occur) at a

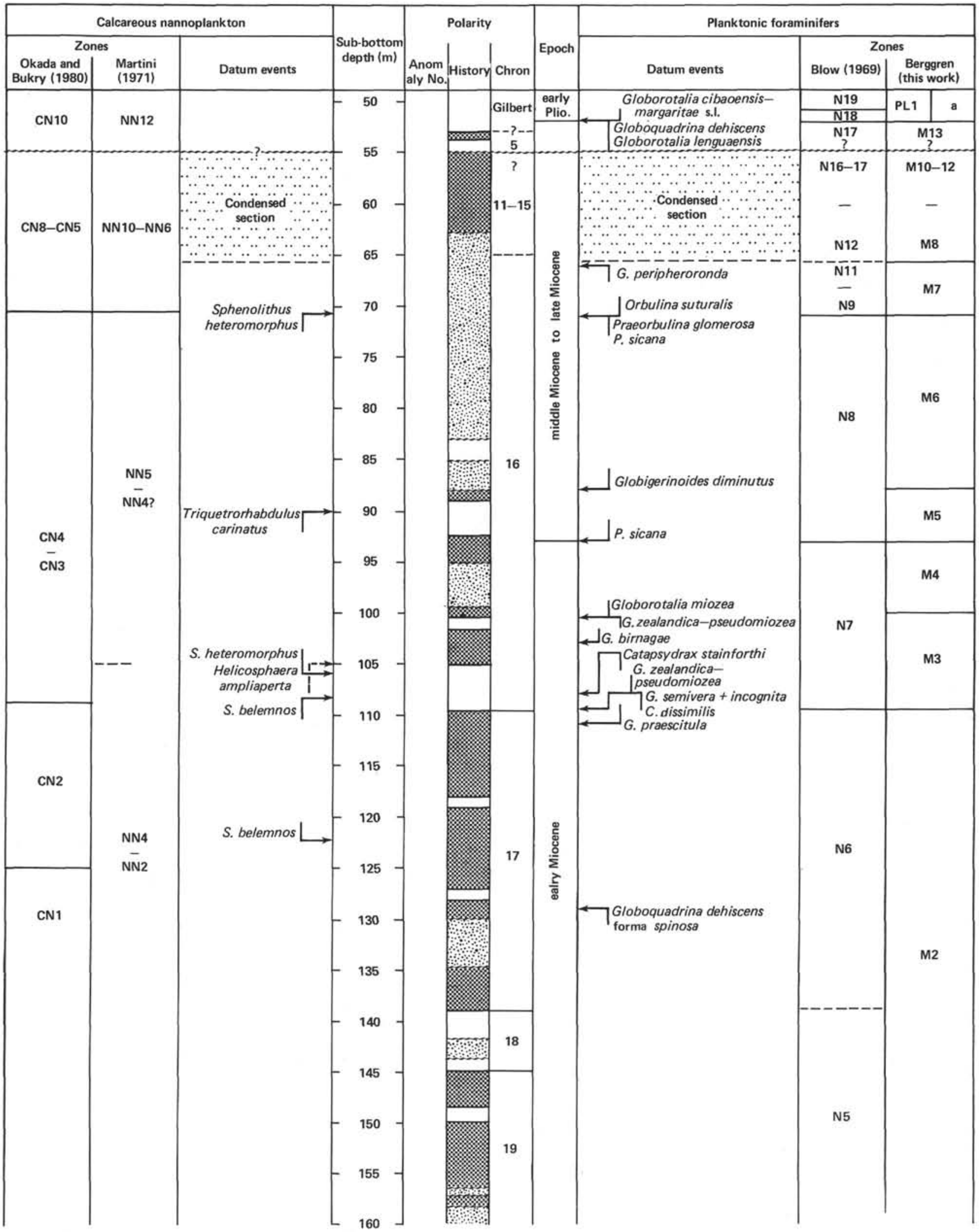


Figure 12. Late Oligocene to late Miocene magnetobiostratigraphic correlations (calcareous plankton), Holes 516 and 516F.

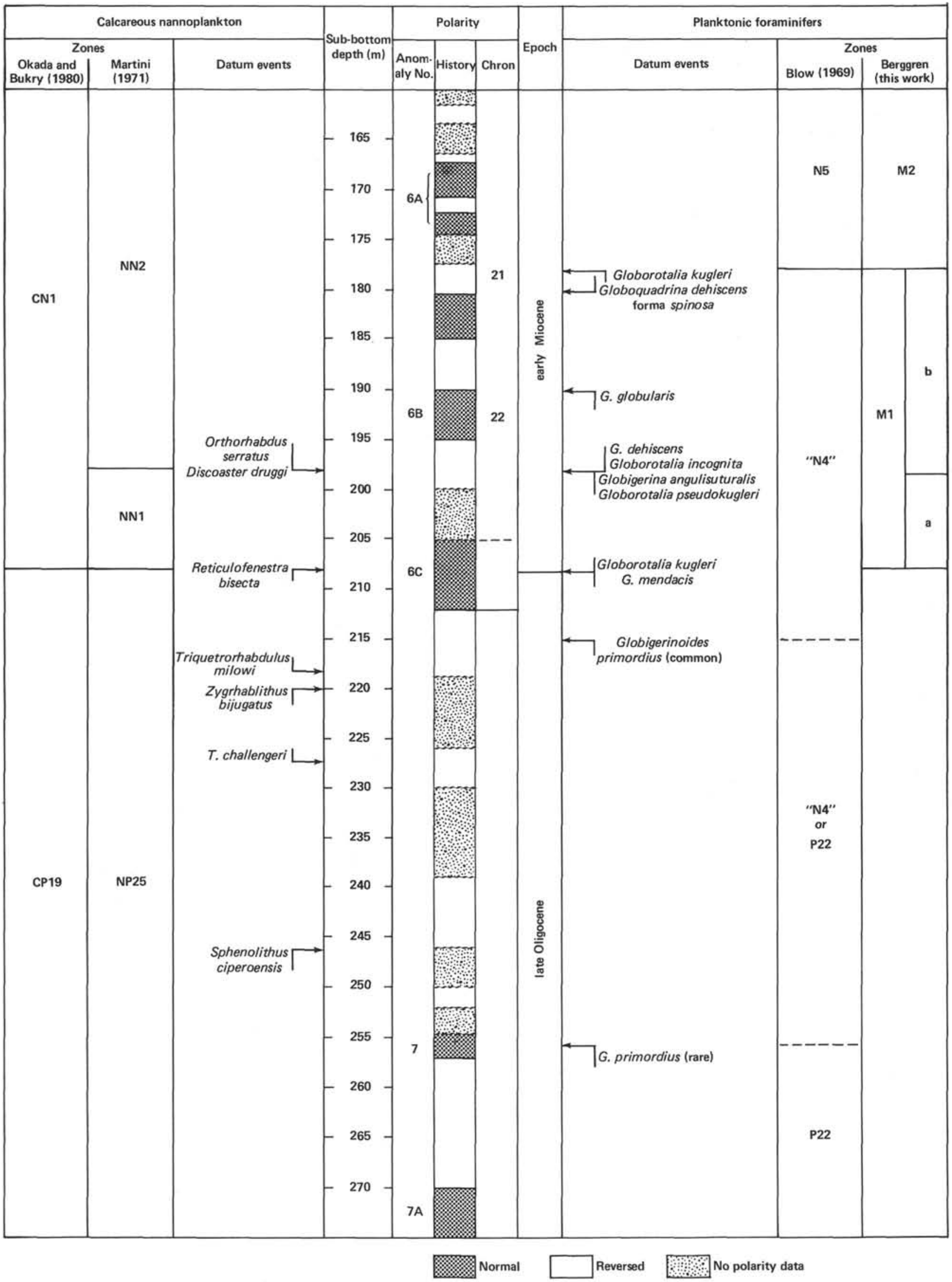


Figure 12. (Continued).

Table 2. Early Miocene calcareous planktonic datum level density in terms of magnetostratigraphy in Hole 516F.

Polarity chron	Calcareous nannoplankton		Planktonic foraminifers	
	FAD	LAD	FAD	LAD
16	1	4	8	8
17	1	0	1	1
18	0	0	0	0
19	0	0	0	0
20	0	0	1	0
21	0	0	1	1
22	2	0	2	3
23	0	1	1	1
Totals	4	5	14	14

Note: FAD = first appearance datum, LAD = last appearance datum.

Table 3. Latest Miocene and Pliocene calcareous planktonic datum level density in terms of magnetostratigraphy in Hole 516.

Polarity chron	Calcareous nannoplankton		Planktonic foraminifers	
	FAD	LAD	FAD	LAD
(1) Brunhes				
(2) Matuyama			1	2
(3) Gauss			4	6
(4) Gilbert	2	7	2	3
(5)	5		3	2
Totals	7	7	10	13

Note: FAD = first appearance datum, LAD = last appearance datum.

stratigraphic level that is uppermost Miocene in terms of biostratigraphy, pre-Gilbert in terms of magnetostratigraphy, and are consistent with magnetobiostratigraphic correlations recorded elsewhere.

Figures 14–17 illustrate the magnetobiochronology for Site 516 planktonic foraminiferal data events. The correlation and estimated magnetochronology of early Miocene low-latitude and midlatitude zonations referred to in these pages are shown in Figure 18. The estimate of 24.2 Ma for the NN1/NN2 boundary of Martini (1971) is based on LAD *Zygrhablithus bijugatus* in Hole 516F; in this paper, we have used LAD *R. bisecta* (23.7 Ma). "Official" criterion for this zonal boundary is LAD of *Helicosphaera recta*, but this form ranges into the Miocene at Site 516 (and elsewhere). The LAD of another form commonly used for this boundary, *S. ciperoensis*, occurs in the upper Oligocene at approximately 24.6 Ma.

Table 4. Latest Oligocene to early Miocene planktonic foraminiferal datum events at DSDP Site 516 and their estimated magnetochronology.

Datum event	Taxa	FAD	LAD	Hole-core-section (level in cm)	Sub-bottom depth (m)	Polarity chron	Estimated age (Ma)
1.	*Orbulina suturalis*	X		516-17-3, 70	72.2	(16)	15.5
2.	*Praeorbulina glomerosa*		X	516-17-3, 70	72.2	(16)	15.5
3.	*P. sicana*		X	516-17-3, 70	72.2	(16)	15.5
4.	*P. glomerosa*	X		516-21-2, 70	88.3	16	16.3
5.	*Globigerinoides diminutus*	X		516-21-2, 70	88.3	16	16.3
6.	*P. sicana*	X		516-22-1, 110	93.1	16	16.6
7.	*Globorotalia miozea*	X		516-24-1, 100	101	16	16.8
8.	*G. zealandica*		X	516-24-1, 100	101.3	16	16.8
9.	*G. pseudomiozea*		X	516-24-1, 100	101.3	16	16.8
10.	*G. birnagae*	X		516-24-3, 100	103	16	17.0
11.	*Catapsydrax stainforthi*		X	516-26-1, 60	108.7	16	17.4
12.	*G. zealandica*	X		516-26-2, 50	109.6	16	17.6
13.	*G. pseudomiozea*	X		516-26-2, 50	109.6	16	17.6
14.	*G. semivera*		X	516-26-2, 50	109.6	16	17.6
15.	*G. incognita*		X	516-26-2, 50	109.6	16	17.6
16.	*G. praescitula*		X	516-26-3, 60	110.7	(16)	17.6
17.	*C. dissimilis*	X		516-26-2, 50	109.6	(16)	17.6
18.	*Globoquadrina dehiscens* (forma *spinosa*)		X	516-30-3, 40	129.1	17	18.3
19.	*Globigerinoides altiaperturus*	X		516-40-1, 70	170	20	20.9
20.	*Globorotalia kugleri*		X	516-42-1, 70	178	21	21.8
21.	*Globoquadrina dehiscens* (forma *spinosa*)	X		516F-2-1, 140	180	21	22.0
22.	*Globigerina globularis*		X	516-43-1, 90	189.8	22	22.8
23.	*Globoquadrina dehiscens* s.s.	X		516F-4-1, 110	198.1	22	23.2
24.	*Globorotalia incognita*	X		516F-4-1, 110	198.1	22	23.2
25.	*Globigerina angulisuturalis*		X	516F-4-1, 110	198.1	22	23.2
26.	*Globorotalia pseudokugleri*		X	516F-4-1, 110	198.1	22	23.2
27.	*G. kugleri*	X		516F-5-1, 110	208.2	23	23.7
28.	*G. mendacis*		X	516F-5-1, 110	208.2	23	23.7
29.	*Globigerinoides primordius* (common)	X		516F-5-6, 150	215	23	24.3
30.	*G. primordius* (rare)	X		516F-10-1, 100	255.6	C7	25.8

Note: FAD = first appearance datum; LAD = last appearance datum; ( ) = inferred chron.

Table 5. Pliocene planktonic foraminiferal datum events at DSDP Hole 516 and their estimated magnetochronology.

Datum event	Taxa	FAD	LAD	Core-section (level in cm)	Sub-bottom depth (m)	Polarity chron	Estimated age (Ma)
1.	*Globorotalia truncatulinoides*	X		3-2, 30	9.2		1.9
2.	*G. obliquus extremus*		X	3-2, 100	9.9	Matuyama	2.1
3.	*G. miocenica*		X	3-2, 100	9.9	(2)	2.1
4.	*Globoquadrina altispira*		X	4-1, 100	12.3		2.5
5.	*Globorotalia multicamerata*		X	4-1, 100	12.3		2.5
6.	*Sphaeroidinella dehiscens* s.s.	X		4-2, 100	13.3		2.8
7.	*Sphaeroidinellopsis* spp.	X		4-2, 100	13.3		2.8
8.	*G. conomiozea*		X	4-3, 100	14.3	Gauss	3.0
9.	*G. conoidea*		X	4-3, 100	14.3	(3)	3.0
10.	*G. inflata*	X		4-3, 100	14.3		3.0
11.	*G. miocenica*	X		5-1, 100	16.7		3.1
12.	*G. crassula*	X		5-1, 100	16.7		3.1
13.	*G. margaritae*		X	5-2, 100	18.2		3.4
14.	*G. nepenthes*		X	6-2, 100	22.1		3.6
15.	*Globorotalia crassaformis* s.l.	X		8-3, 120	33.0		4.2
16.	*Globigerinoides siegliei*		X	9-1, 120	34.5	Gilbert	4.3
17.	*Globorotalia puncticulata* s.l.	X		9-2, 100	35.3	(4)	4.4
18.	*G. cibaoensis*		X	9-2, 100	35.3		4.4
19.	*Globigerinoides conglobatus*	X		13-1, 115	52.1		5.4
20.	*Globorotalia cibaoensis–margaritae* s.l.	X		13-2, 115	53.5	(5)	5.4
21.	*Globoquadrina dehiscens*		X	13-2, 115	53.5		5.4
22.	*Globorotalia lenguaensis*		X	13-2, 115	53.5		5.4

Note: FAD = first appearance datum, LAD = last appearance datum.

Table 6. Latest Oligocene to early Miocene calcareous nannoplankton datum events at DSDP Site 516 and their estimated magnetochronology.

Datum event	Taxa	FAD	LAD	Hole-core-section (level in cm)	Sub-bottom depth (m)	Polarity chron	Estimated age (Ma)
1.	*Sphenolithus heteromorphus*		X	516-17-2, 110	71.1	(16)	15.5
2.	*Helicosphaera ampliaperta*		X	516-25-2, 70	105.9	16	17.0
3.	*S. heteromorphus*	X		516-25-2, 70	105.9	16	17.0
4.	*S. belemnos*		X	516-26-1, 60	108.7	16	17.1
5.	*S. belemnos*	X		516-29-1, 135	122.6	17	17.4
6.	*Discoaster druggi*	X		516F-3-5, 100	195	22	23.2
7.	*O. serratus*	X		516F-4-1, 100	198	22	23.3
8.	*Reticulofenestra bisecta*		X	516F-5-1, 100	208	23	23.7
9.	*Triquetrorhabdulus milowii*	X		516F-6-2, 17	218	23	24.3
10.	*Zyghrablithus bijugatus*		X	516F-7-1, 96	227	23	24.6
11.	*T. challengeri*	X		516F-7-1, 96	227	23	24.6
12.	*S. ciperoensis*		X	516F-9-1, 98	246	23	24.9

Note: FAD = first appearance datum, LAD = last appearance datum, ( ) = inferred chron.

Table 7. Pliocene calcareous nannoplankton datum events at DSDP Hole 516 and their estimated magnetochronology.

Datum event	Taxa	FAD	LAD	Core-section (level in cm)	Sub-bottom depth (m)	Polarity chron	Estimated age (Ma)
1.	*Reticulofenestra pseudoumbilica*		X	5-3, 100	19.7		3.46
2.	*Sphenolithus abies*		X	5-3, 100	19.7		3.46
3.	*S. neoabies*		X	5-3, 100	19.7	Gilbert	3.46
4.	*Amaurolithus delicatus*		X	6-1, 100	21.1		3.6
5.	*A. tricorniculatus*		X	6-1, 100	21.1	(4)	3.6
6.	*Ceratolithus rugosus*	X		9-2, 100	35.8		4.4
7.	*C. acutus*		X	9-3, 100	37.3		4.48

Note: FAD = first appearance datum, LAD = last appearance datum.

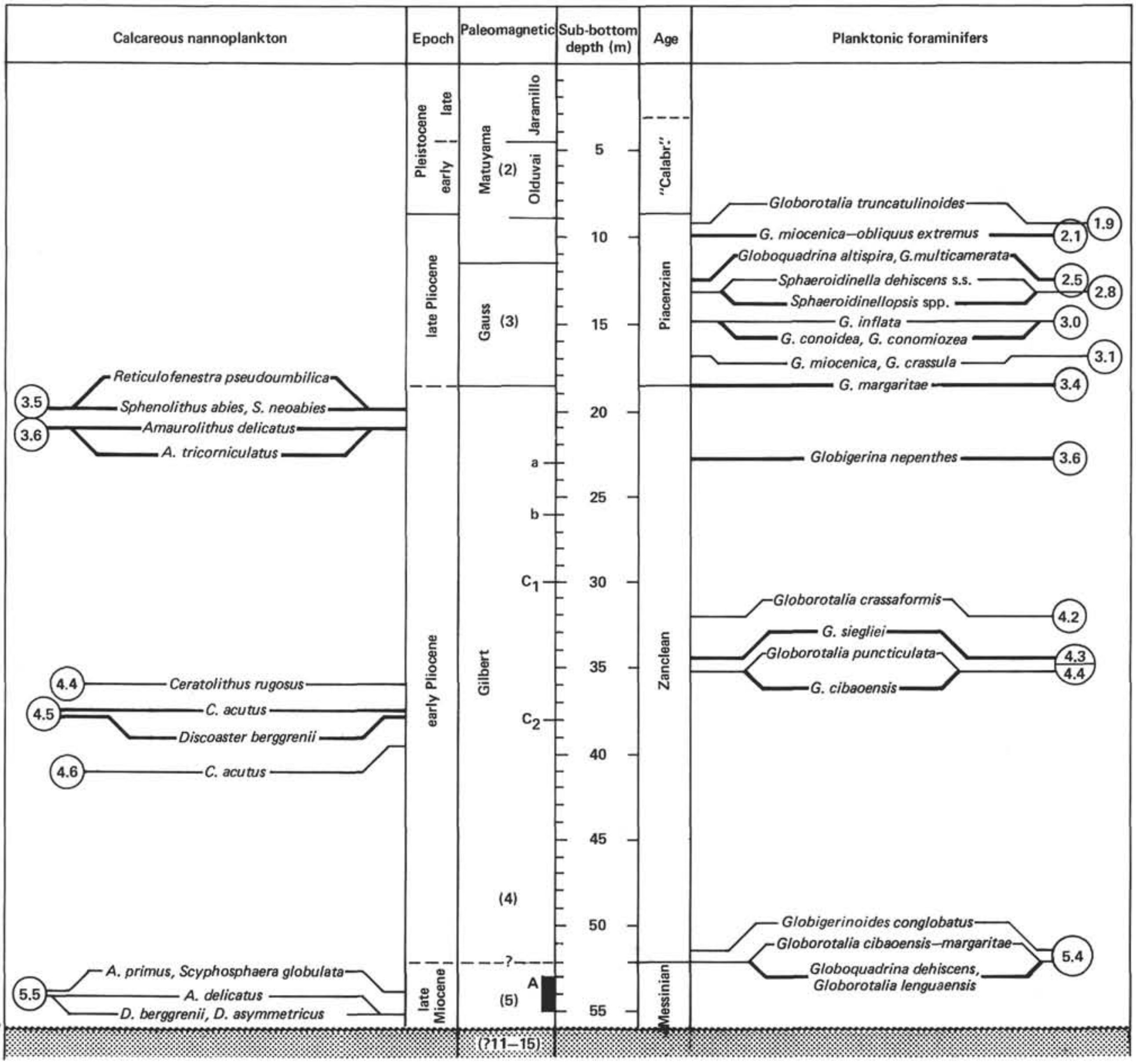


Figure 13. Early Pliocene to Pleistocene magnetobiostratigraphic correlations (calcareous nannoplankton), Hole 516. Estimated ages (in Ma) of datum levels are encircled; the thin line indicates the first appearance datum; the heavy line indicates the last appearance datum.

Thus, age estimates for this boundary will vary considerably based on the different criteria. Similarly, the variable occurrence of *Globigerinoides* (before or within the range of *Globorotalia kugleri*) renders Zone N4 (Blow, 1969) inoperable.

Taxonomic Note

The *Globorotalia miozea-conomiozea* group is numerically and biostratigraphically important in the upper lower Miocene to lower Pliocene of the Rio Grande Rise (Site 516) as well as in other midlatitude regions of the world. The forerunners of this group are also common and biostratigraphically important in the lower Miocene at this site. Because they are less well known than their better-studied descendants and because some taxonomic confusion surrounds their correct identity, we present a brief discussion for clarification. The reader is referred to Plates 4 and 5 and Figure 19 in connection with the following discussion.

Walters (1965) distinguished two lineages of globorotaliids with a virtually synchronous origin in the early Miocene Awamoan of New Zealand. These were the *G. zealandica* lineage and the *G. miozea* lineage.

The *G. zealandica* lineage was thought to have had its origin with the relatively long-ranging *G. zealandica incognita*, a relatively small, four-chambered form with a lobate periphery (see Fig. 19, No. 6a–j). An increase in size and degree of inflation of the ventral side, and the development of a secondary thickening of the test wall as seen in *G. miozea* was considered definitive in recognizing the descendant form *G. pseudomiozea* (see Fig. 19, No. 6k–t). At virtually the same time, the thin-

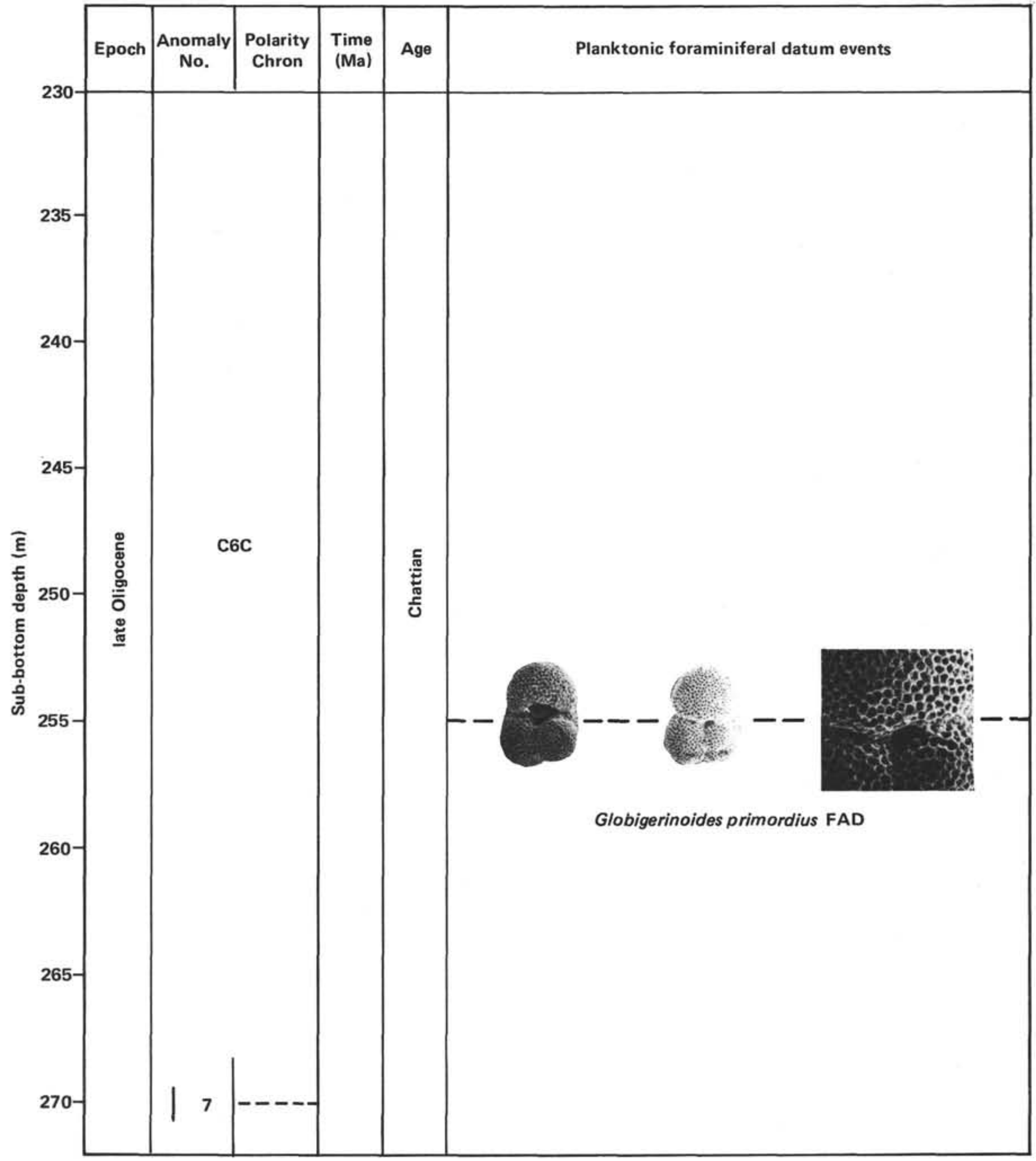


Figure 14. Late Oligocene planktonic foraminiferal datum magnetobiochronology in Hole 516F. FAD = first appearance datum.

walled, anguloconical, four-chambered to five-chambered *G. zealandica* s.s. appeared (Fig. 19, No. 395–397); all morphologic gradations occur between the two forms. Distinction between the two was retained only because *G. zealandica* morphotypes were said to have ranged sporadically into the Altonian after the disappearance of the *G. pseudomiozea* morphotype.

Jenkins (1967) described *G.* (*Turborotalia*) *nana pseudocontinuosa* from the Otaian, *Globigerina woodi connecta* Zone of the early Miocene (= Aquitanian) and subsequently (1971) showed that it had a stratigraphic range that essentially spanned the early Miocene. In the latter paper (1971), he also recorded *Globorotalia incognita* from the Awamoan of New Zealand.

However, an examination of the illustrations by Jenkins (1971) of *pseudocontinuosa* and *incognita* (see Fig. 19, No. 336–341 and 374–376, respectively) reveals the following:

1) *G. pseudocontinuosa* Jenkins, 1967 = *G. zealandica incognita* Walters, 1965. They are identical in every way (compare for instance, Fig. 19, No. 339–341 and 6a–c).

2) *G. incognita* of Jenkins (1971) is *not* the same as *G. zealandica incognita* Walters, 1965. The illustrations by Jenkins (see Fig. 19, No. 374–376) agree well with those by Walters (1965) of *G. zealandica pseudomiozea* (see Fig. 19, No. 6k–t). Compare for instance, in particular, Figure 19, No. 374–376 and 6p–r.

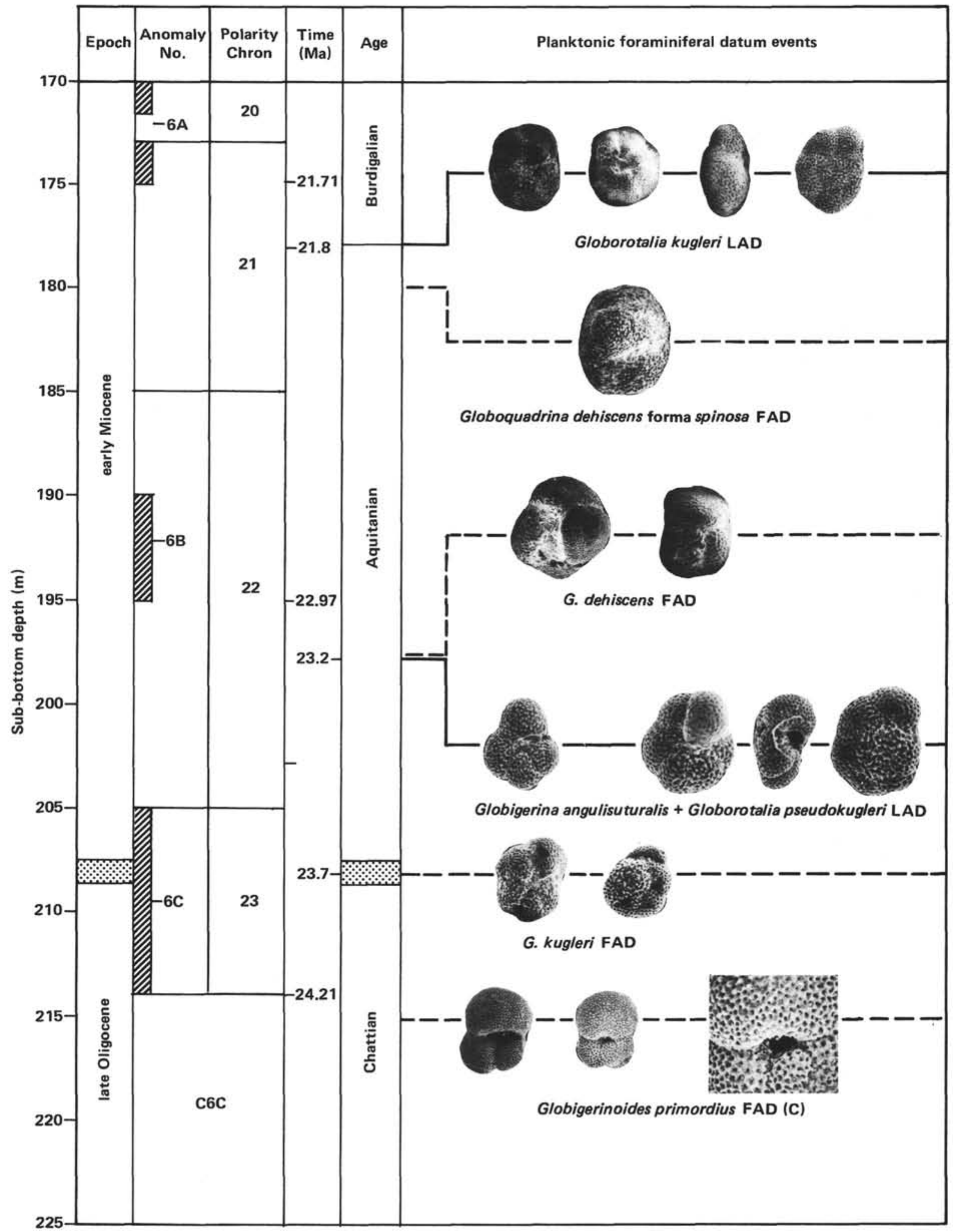


Figure 15. Latest Oligocene to earliest Miocene planktonic foraminiferal datum magnetobiochronology in Holes 516 and 516F. C = common; LAD = last appearance datum; FAD = first appearance datum.

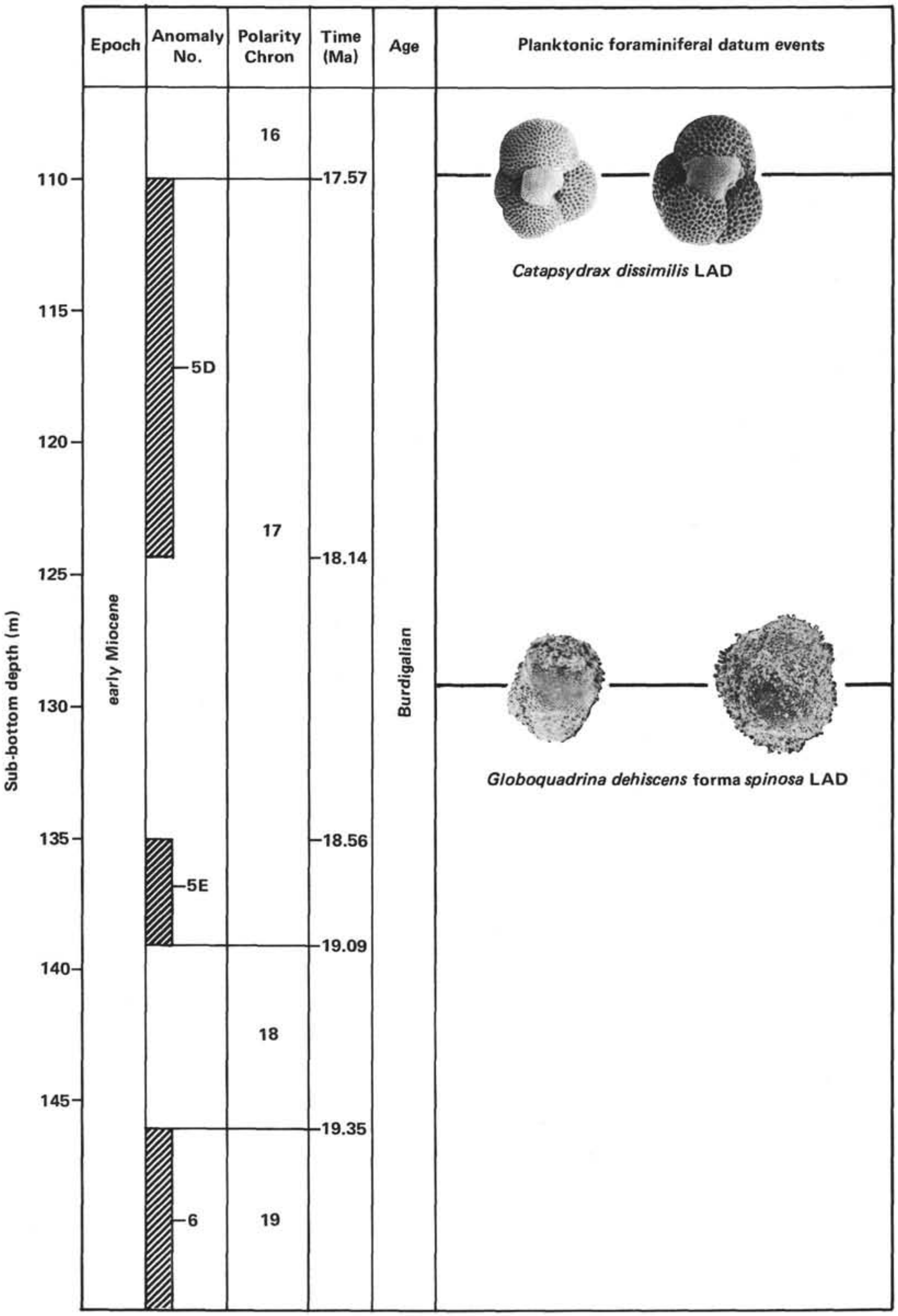


Figure 16. Early Miocene planktonic foraminiferal datum magnetobiochronology in Hole 516. LAD = last appearance datum.

Thus the correct name for the relatively long-ranging, pre-*zealandica* taxon in the lower Miocene is *G. incognita.* (*G. semivera* is a closely related form and distinguished primarily on the basis of its five chambers (Jenkins, 1971; see Fig. 19, No. 324–344). *Globorotalia zealandica-pseudomiozea* morphotypes developed abruptly in the middle of the early Miocene from *G. incognita* as described by Walters (1965). In the samples from Site 516, these forms appear at the base of Zone N7 near the Chron 16/17 boundary.

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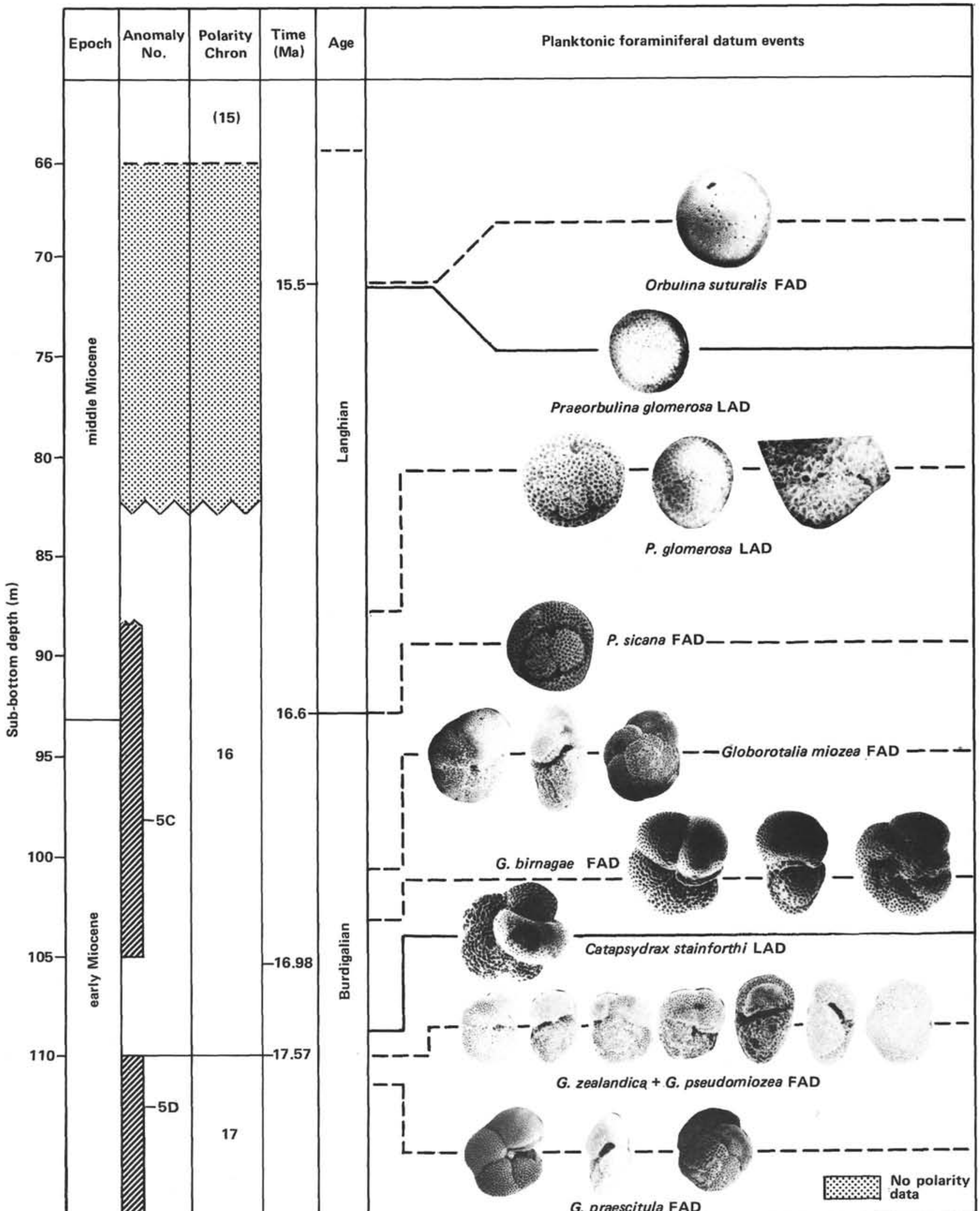

Figure 17. Early-middle Miocene planktonic foraminiferal datum magnetobiochronology in Hole 516. FAD = first appearance datum; LAD = last appearance datum.

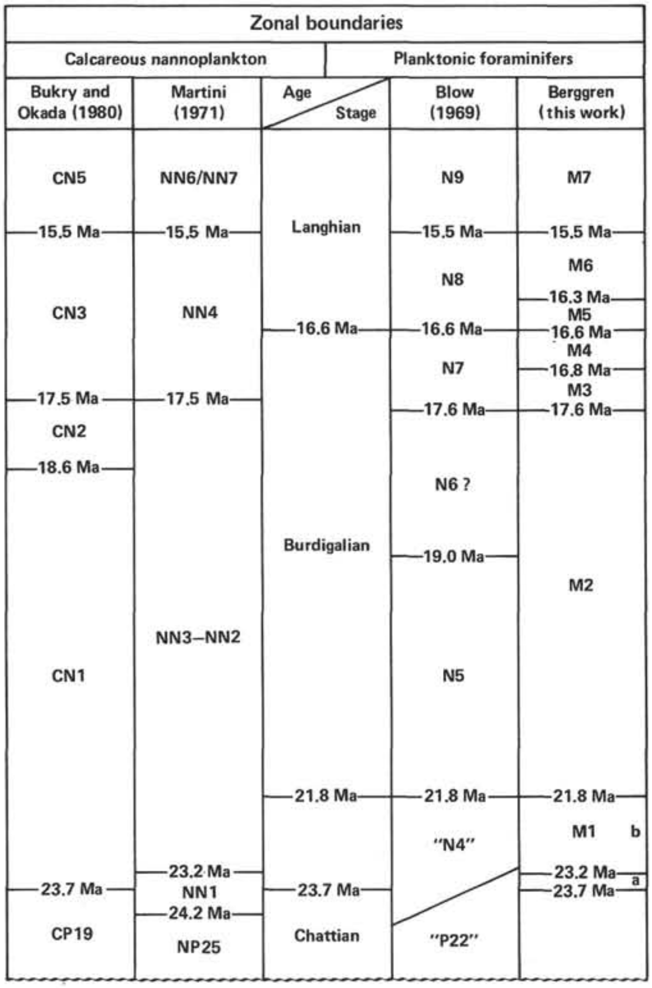

Figure 18. Early Miocene low-latitude and midlatitude planktonic zonal correlations; estimated magnetochronology is based on time scale of Berggren et al. (in press). Calc. nannopl. = calcareous nannoplankton; plank. foram. = planktonic foraminifers. See text for discussion.

ples and continued interest and encouragement. We extend our thanks to our colleague R. Z. Poore (Reston, Virginia) with whom we exchanged ideas and unpublished data in the course of our respective studies on DSDP Legs 72 and 73. This type of cooperation has significantly improved our interpretation of the data and has played no small part in the ideas expressed here. Finally, we thank Richard Poore and Edith Vincent (La Jolla, California) for their critical reviews of an early draft of this report.

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NOTE TO THE PLATES

The zonal correlations in the figures are those of Blow (1969). The correlations with the new zonation developed within this chapter are identified in Figure 12.

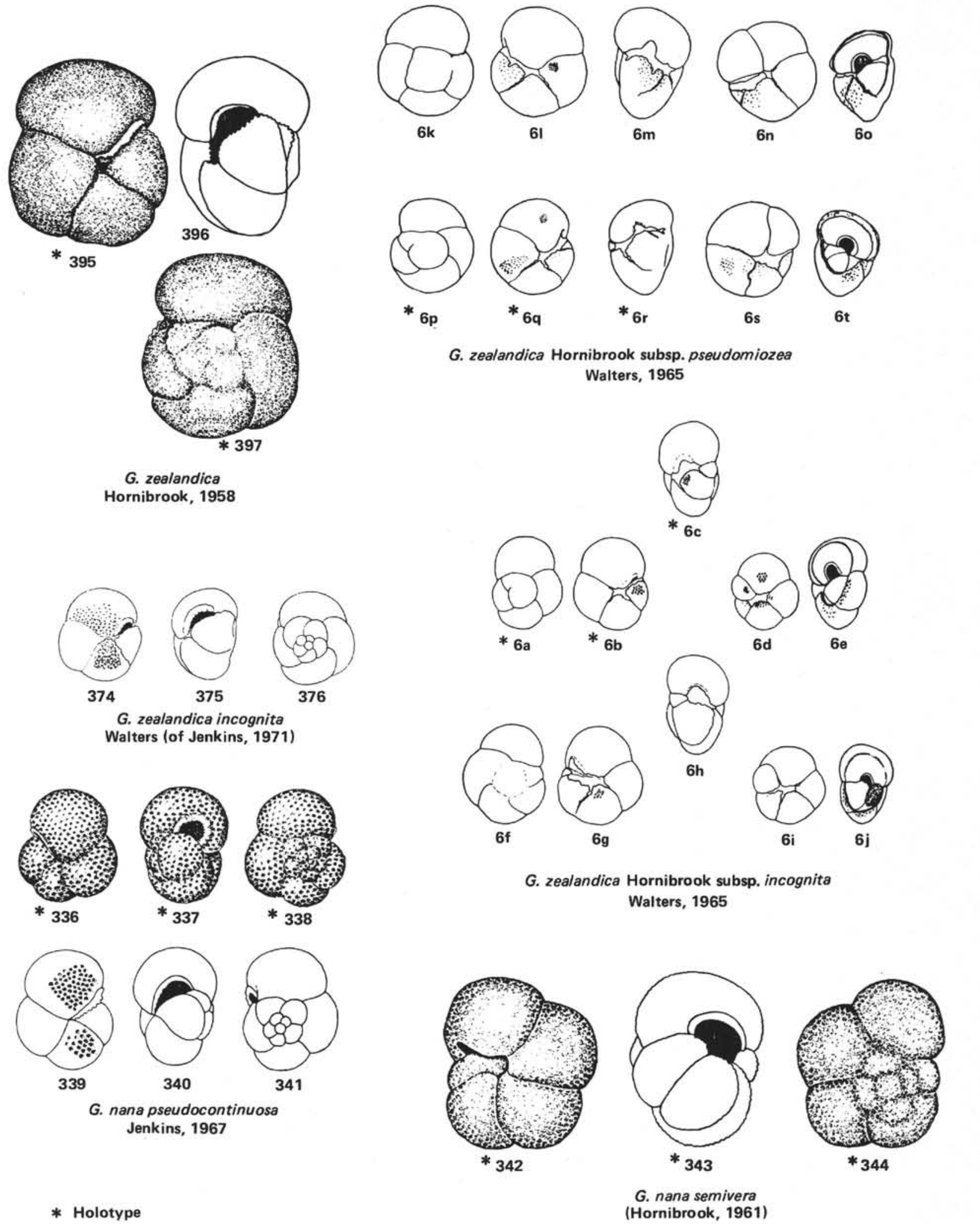

Figure 19. Early Miocene members of the *Globorotalia miozea* lineage. See text for discussion.

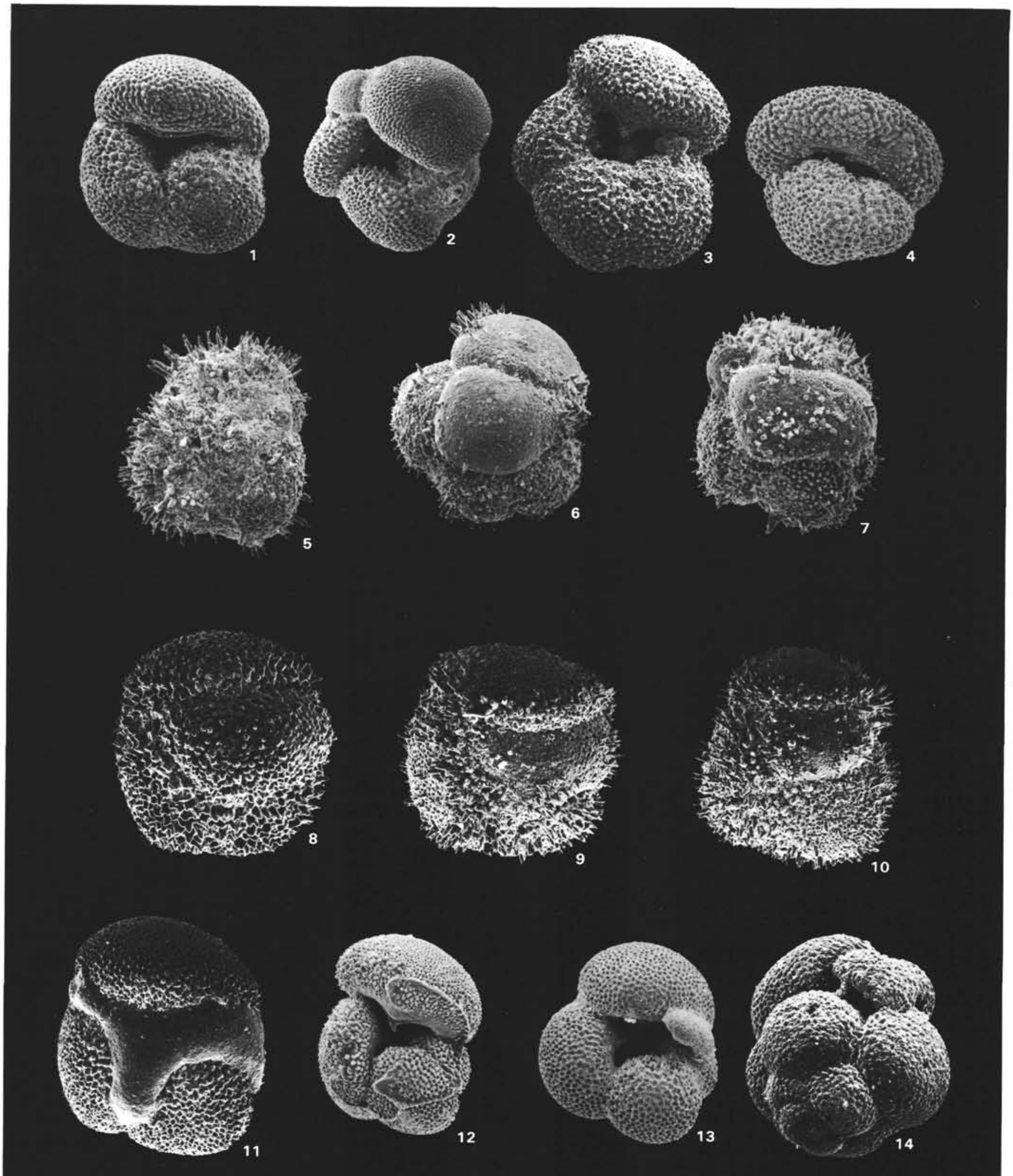

Plate 1. **1.** *Globoquadrina praedehiscens* Blow, Sample 516-39-1, 80–82 cm, ×55, Zone N5. **2–4.** *Globoquadrina dehiscens* (Chapman, Parr and Collins), Zone N5, (2) Sample 516-39-1, 80–82 cm, ×50, (3) Sample 516-35-2, 60–62 cm, ×75, (4) Sample 516-38-2, 70–72 cm, ×70. **5–10.** *Globoquadrina dehiscens* (Chapman, Parr and Collins), "spinose variant;" note varying strength of surface spinosity and perforate, weakly to densely spinose umbilical bulla, (5–7) Sample 516-36-1, 70–72 cm, Zone N5, (5, ×75; 6, ×50; 7, ×60), (8–10) Sample 516-32-3, 90–92 cm, Zone N6, (8, ×100; 9, ×75; 10, ×60). **11.** *Globoquadrina dehiscens* (Chapman, Parr and Collins), Sample 516-32-3, 90–92 cm, ×75, Zone N6, note finely perforate sutural bulla. **12.** *Globoquadrina baroemoenensis* Le Roy, Sample 516-39-1, 80–82 cm, ×50, Zone N5. **13.** *Globoquadrina larmeui* Akers, Sample 516-36-1, 70–72 cm, ×65, Zone N5. **14.** *Globoquadrina altispira*, Sample 516-35-3, 60–62 cm, ×50, Zone N5.

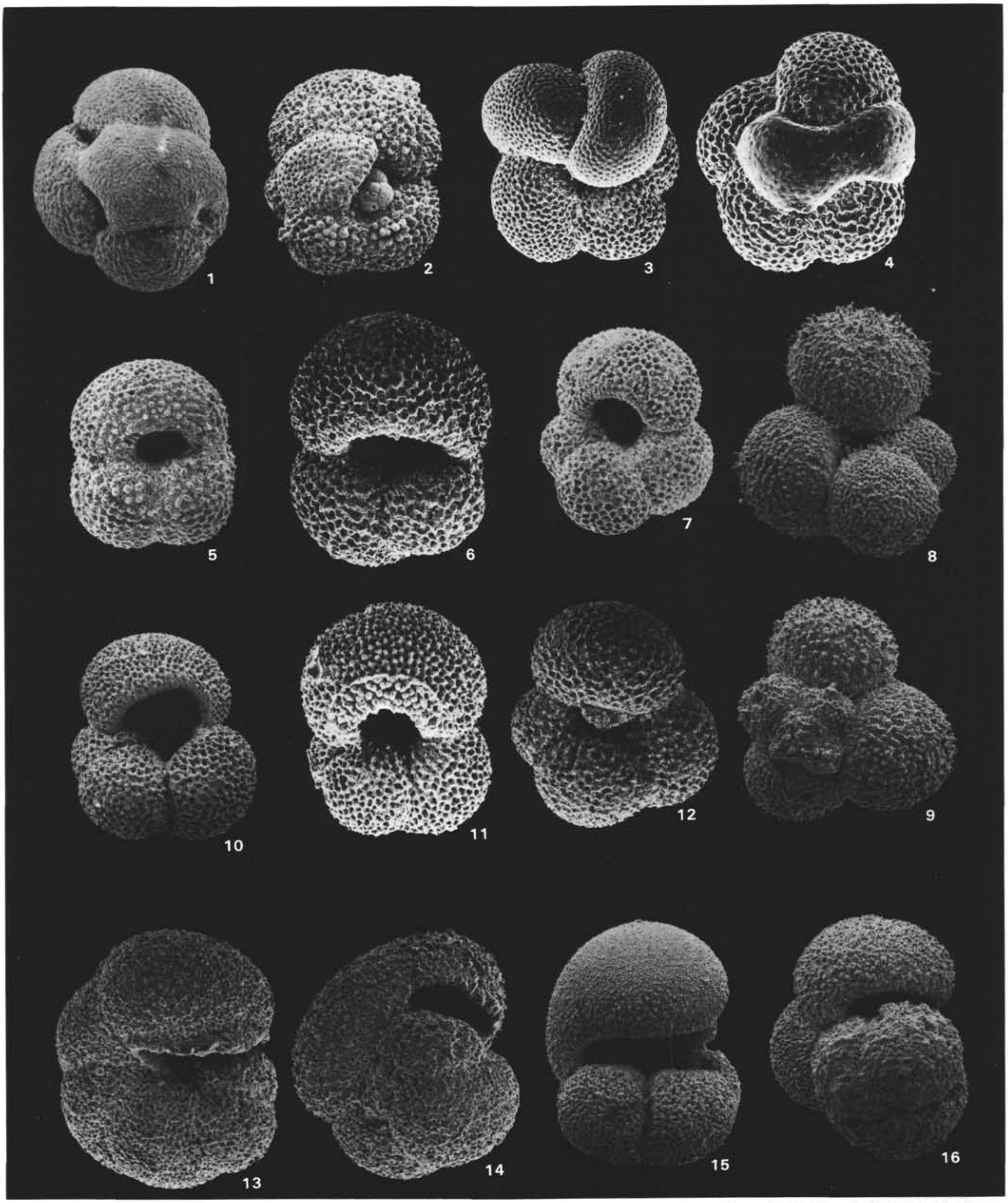

Plate 2. **1.** *Catapsydrax dissimilis* Bolli, Sample 516-36-2, 70–72 cm, ×55, Zone N5. **2.** *Catapsydrax unicavus* Bolli, Sample 516-35-2, 60–62 cm, ×60, Zone N5. **3.** *Catapsydrax praestainforthi*, Sample 516-34-3, 90–92 cm, ×100, Zone N5. **4.** *Catapsydrax stainforthi* Bolli, Loeblich, and Tappen, Sample 516-27-3, 70–72 cm, ×100, Zone N6. **5, 7.** Sample 516-38-2, 70–72 cm, ×80, Zone N5, (5) *Globigerina connecta* Jenkins, (7) *Globigerina woodi* Jenkins. **6, 11.** Sample 516-34-2, 20–22 cm, ×100, Zone N5, (6) *Globigerina brazieri*, (11) *Globigerinoides subquadratus* Brönnimann. **8–9, 15–16.** Sample 516-25-2, 70–72 cm, Zone N6, (8–9) *Globigerina eamesi* Blow, ×85, (15–16) *Globigerinopsis* sp., ×55. **10.** *Globigerinoides altiaperturus* Bolli, Sample 516-35-3, 60–62 cm, ×100, Zone N5. **12.** *Globorotaloides suteri* Bolli, Sample 516-42-2, 70–72 cm, ×100, Zone N4. **13–14.** *Globigerinopsis* sp., Sample 516-26-1, 60–62 cm, Zone N7 (13) ×85, (14) ×65.

Plate 3. **1-33.** *Globorotalia kugleri* Bolli, Sample 516-43-1, 92–94 cm, ×140, Zone N4. **4–5.** *Globorotalia semivera* Jenkins, Sample 516-40-2, 70–72 cm, ×110, Zone N5. **6–7.** *Globorotalia incognita* Walters, Sample 516-39-1, 80–82 cm, Zone N5, (6) ×120, (7) ×145. **8–10.** *Globorotalia siakensis* Le Roy, Sample 516-38-2, 70–72 cm, Zone N5, (8–10) ×115, (9) ×70. **11–13.** *Globorotalia* sp. aff. *G. peripheroronda* Blow and Banner, Sample 516-27-3, 70–73 cm, ×100, Zone N6. **14–16.** *Globorotalia peripheroronda* Blow and Banner, Sample 516-18-1, 90–91 cm, ×150, Zone N11.

Plate 4. *Globorotalia zealandica* group. **1-4, 15.** Sample 516-26-2, 50-52 cm, Zone N6, ×100, (1) *Globorotalia semivera* Jenkins, (2-4, 15) *Globorotalia zealandica* Hornibrook, (2-4, "Early transitional variants," note the retention of essentially same chamber shape as in ancestral form *G. semivera* except for development of low, anguloconical final chamber; 15, note development of encrustation upon a test with essentially the same shape as Figure 8 specimen). **5-8.** *Globorotalia zealandica* Hornibrook, Sample 516-26-1, 60-62 cm, ×100, Zone N6, note variation in size of final chamber (Figs. 5-6 versus 8). **9-14.** *Globorotalia zealandica* Hornibrook, Sample 516-25-2, 70-72 cm, Zone N6 (9) ×75, (10) ×80, (11) ×70, (12) ×55, (13) ×100, (14) ×80.

Plate 5. **1, 5–6.** Sample 516-26-2, 50–52 cm, Zone N6, ×100, (1) *Globorotalia incognita* Walters, (5–6) *Globorotalia* sp. ex inter. *G. incognita* Walters–*G. pseudomiozea* Walters. **2–4.** *Globorotalia* sp. ex inter. *G. incognita* Walters–*G. pseudomiozea* Walters, Sample 516-26-3, 60–62 cm, ×100 Zone N6. **7–9.** *Globorotalia* sp. ex inter. *G. incognita* Walters–*G. pseudomiozea* Walters, Sample 516-26-1, 60–62 cm, Zone N6, (7) ×90, (8) ×100, (9) ×90. **10–17.** *Globorotalia pseudomiozea* Walters, Sample 516-25-2, 70–72 cm, Zone N6; note development of tight (involute) coiling mode, subconical chambers, restriction of the aperture, and encrustation of the test in this species; (10) ×85; (11, 13–17) ×100, (12) ×95.

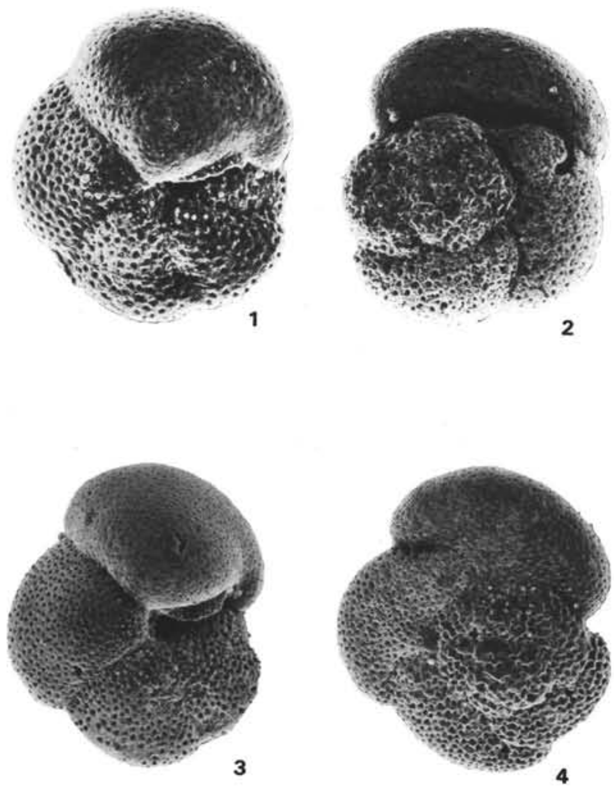

Plate 6. **1–4.** *Globorotalia praescitula* Blow, Zone N6, (1–2) Sample 516-28-3, 70–72 cm, ×140, (3–4) Sample 516-27-3, 70–72 cm, ×100.