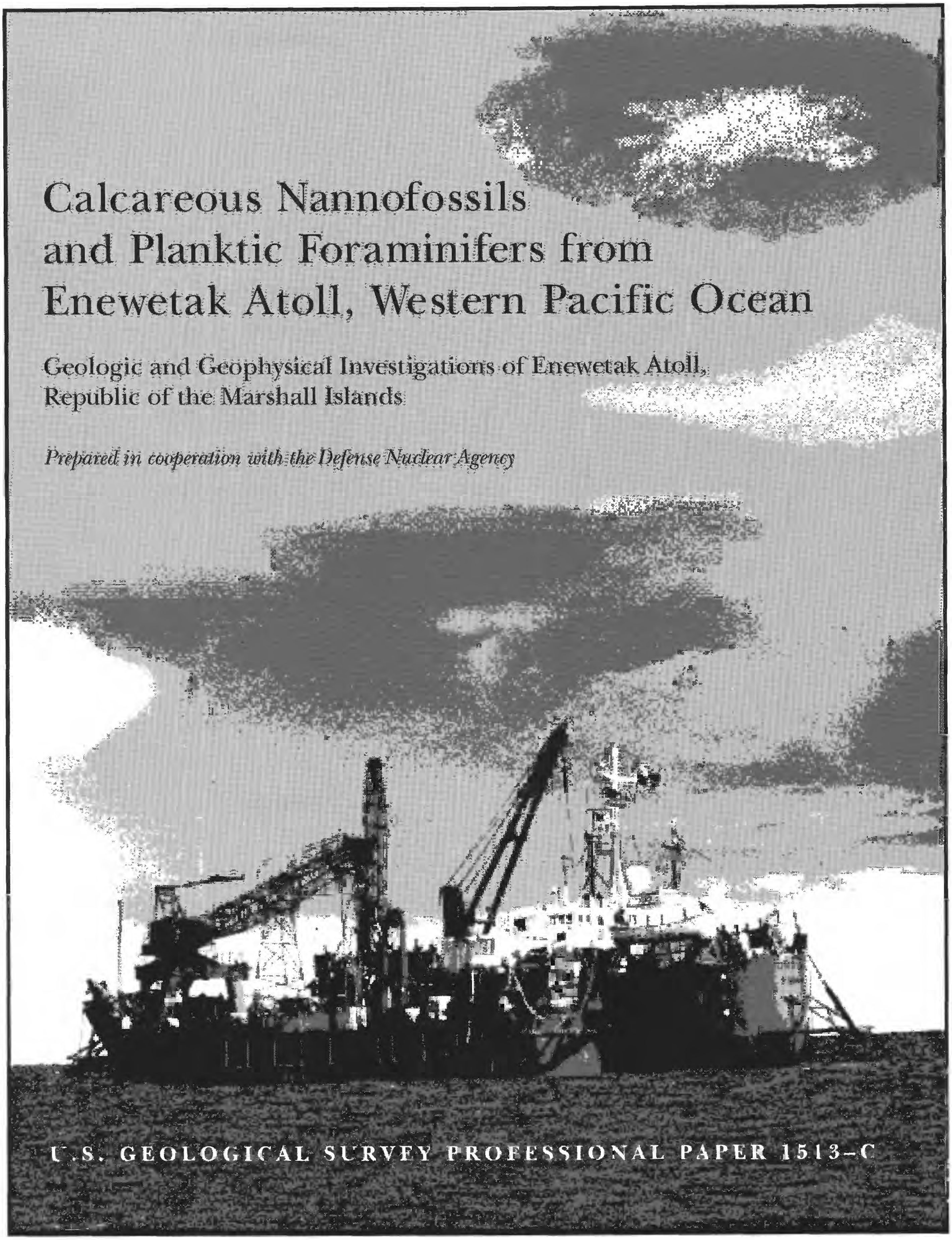

Calcareous Nannofossils and Planktic Foraminifers from Enewetak Atoll, Western Pacific Ocean

Geologic and Geophysical Investigations of Enewetak Atoll, Republic of the Marshall Islands

Prepared in cooperation with the Defense Nuclear Agency

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1513-C

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By LAUREL M. BYBELL *and* RICHARD Z. POORE

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CALCAREOUS NANNOFOSSILS AND PLANKTIC FORAMINIFERS FROM ENEWETAK ATOLL, WESTERN PACIFIC OCEAN

By LAUREL M. BYBELL and RICHARD Z. POORE

ABSTRACT

Calcareous nannofossils and planktic foraminifers were examined from five boreholes that were sampled as part of the Pacific Enewetak Atoll Crater Exploration (PEACE) Program and from two previously drilled wells in the Enewetak area. Both calcareous nannofossils and planktic foraminifers were sparse and poorly preserved in these samples, but by combining all available age data from these two groups with a local benthic biostratigraphy based on ostracodes and benthic foraminifers, it was possible to obtain reliable ages for many of these sediments. The oldest sediments in the PEACE Program samples that were dated with planktic microfossils are middle Miocene in age (calcareous nannofossil Zones NN 5–7). Late Miocene Zones NN 9 and NN 11 also are definitely represented. There is a thick early Pliocene section at Enewetak, which cannot be dated any more accurately than somewhere within Zones NN 12–15, and a thin, poorly constrained late Pliocene section. Zone NN 19, which spans the Pliocene-Pleistocene boundary, is present at Enewetak, and it is overlain by middle to late Pleistocene sediments of undifferentiated Zones NN 20–21.

INTRODUCTION

PURPOSE AND SCOPE

Boring of the carbonate sequence at the northern end of Enewetak Atoll, Republic of the Marshall Islands, was conducted in 1985, as part of the Pacific Enewetak Atoll Crater Exploration (PEACE) Program (fig. 1). The overall goal of the program was to characterize physical effects of large-scale nuclear blasts, which were conducted in the early 1950's, on the sediments of the atoll. Most boreholes were drilled to several hundred feet subbottom, although a few were deeper than 1,000 ft, and one was drilled to 1,600 ft subbottom. Samples from PEACE Program cores and cores taken during earlier investigations of Enewetak Atoll were examined for microfossils to provide a refined correlation for the upper sedimentary sequence at Enewetak. The shallow-water reef, back-reef, and lagoonal sequence sampled at Enewetak commonly yielded abundant benthic microfossils (ostracodes, larger foraminifers, and smaller benthic foraminifers). These benthic microfossils, primarily ostracodes and benthic foraminifers, were used to develop a local biostratigraphy that proved useful for correlating and interpreting subsurface units sampled during the PEACE Program (Cronin and others, 1986; Wardlaw and Henry, 1986, this volume).

In contrast, calcareous nannofossils and planktic foraminifers occur sporadically and in low abundance at Enewetak and were not useful for detailed correlations among cores. However, some samples did yield stratigraphically diagnostic assemblages, and these samples made dating intervals within several Enewetak boreholes possible.

In this report we document the occurrences of stratigraphically diagnostic planktic microfossils in samples from Enewetak (generally referred to as core) and outline our rationale for incorporating all available diagnostic planktic assemblages into a composite sequence that was used to date the Enewetak benthic zonation.

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MATERIALS AND METHODS

A total of 32 boreholes were drilled at Enewetak as part of the PEACE Program. Many samples from every

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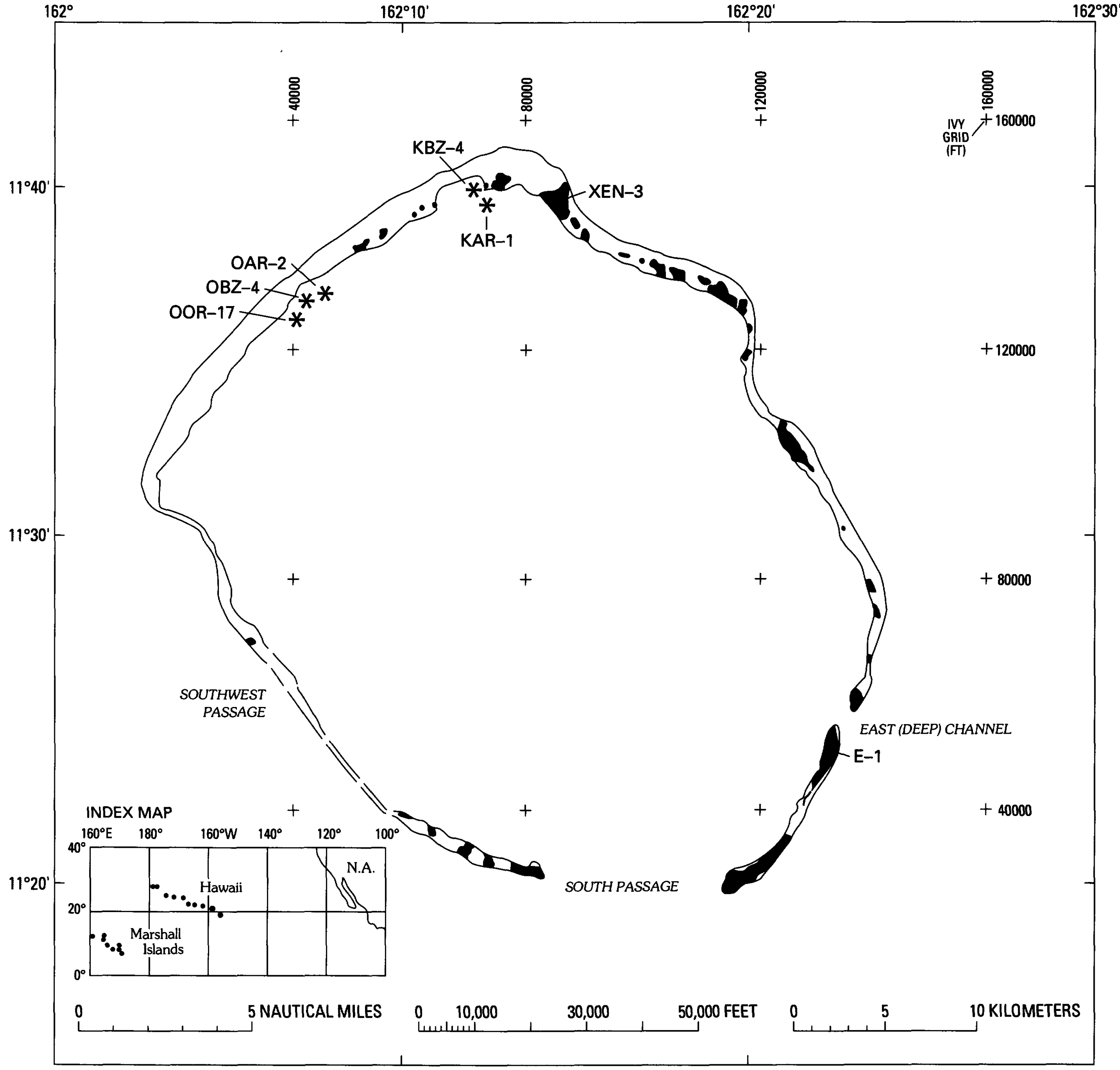


FIGURE 1.—Location of Enewetak Atoll and position of the seven boreholes discussed in this paper.

borehole were examined, but stratigraphically diagnostic planktic assemblages were found only in five cores: KAR-1, OAR-2 and 2A, OOR-17, KBZ-4, and OBZ-4 (fig. 1). The first three boreholes are reference holes that were drilled into undisturbed sediments away from areas affected by large-scale nuclear blasts. Cores KBZ-4 and OBZ-4 are moderately deep boreholes that were drilled in the center of two large blast-induced craters. In addition to the PEACE boreholes, XEN-3, a core which was taken on Engebi Island during the Exploration Program on Enewetak (EXPOE) in 1973–74, yielded diagnostic planktic assemblages. Planktic microfossils also were examined from one deep interval in the Enewetak E-1 hole, which was drilled in 1952 as part of an Atomic Energy Commission test program of the Los Alamos Scientific Laboratory.

Information on the PEACE and EXPOE cores, including location, details of coring, and lithologic descriptions, is in Wardlaw and Henry (1986, this volume). A description of the E-1 hole is in Schlanger (1963). Processing techniques for planktic microfossil samples are outlined in Cronin and others (1986).

MICROFOSSIL ZONATIONS AND DATUMS

In general, planktic microfossils are sparse, poorly preserved, or absent in most samples that we examined from the Enewetak cores. For example, our most productive calcareous nannofossil samples yielded one or two specimens per field of view at 500 × magnification, and most taxa present were stratigraphically long-ranging and solution-resistant species. When found, most planktic foraminiferal assemblages contained sparse, poorly preserved specimens of long-ranging species of *Globigerinoides*, such as *G. sacculifer*, *G. ruber*, or *G. obliquus*. Therefore, routinely using a single published calcareous nannofossil or planktic foraminiferal zonation such as Martini (1971) to interpret the assemblages was impossible. Instead, we used a variety of published and unpublished sources to assemble a group of biostratigraphic events (or biostratigraphic datums) that we found useful during this study.

These biostratigraphic events must be interpreted conservatively in the Enewetak boreholes because the sporadic occurrence of planktic microfossils makes observing an actual FAD (first appearance datum) or LAD (last appearance datum) highly unlikely. Thus, the observed lower and upper limits of taxa in Enewetak cores are used to set limits on the biostratigraphic assignment of samples; they are not interpreted as actual FAD's and LAD's.

We have prepared two lists of biostratigraphic events that proved to be useful in dating Enewetak samples, one for calcareous nannofossils and one for planktic foraminifers. Asterisks indicate taxa that have been used to formally define zone boundaries in the calcareous nannofossil zonations of Martini (1971) and Bukry (1973, 1975) or in the planktic foraminiferal zonation of Blow (1969).

CALCAREOUS NANNOFOSSILS

LAD **Pseudoemiliania lacunosa*—top Zone NN 19—Pleistocene (Martini, 1971)

LAD *Calcidiscus macintyrei*—lower part of Zone NN 19—early Pleistocene (Gartner, 1977a)

FAD *Gephyrocapsa* large species—near base of Zone NN 19—latest Pliocene (Berggren and others, 1985)

LAD *Sphenolithus abies* complex or genus *Sphenolithus*—near or at top of Zone NN 15—early Pliocene (Martini, 1971; Bukry, 1973; Perch-Nielsen, 1985)

LAD **Reticulofenestra pseudoumbilica*—top Zone NN 15—early Pliocene (Martini, 1971; Bukry, 1973)

FAD *Pseudoemiliania lacunosa*—near top of Zone NN 15—early Pliocene (Perch-Nielsen, 1985)

LAD **Discoaster quinqueramus*—top Zone NN 11—late Miocene (Martini, 1971; Bukry, 1973; Perch-Nielsen, 1985)

LAD *Discoaster berggrenii*—upper part of Zone NN 11—late Miocene (Bukry, 1973; Perch-Nielsen, 1985)

LAD *Discoaster neohamatus*—sporadic occurrence up into mid-Zone NN 11—late Miocene (Martini, 1971; Bukry, 1973; Perch-Nielsen, 1985)

FAD **Discoaster berggrenii*—base Zone NN 11—late Miocene (Bukry, 1973; Perch-Nielsen, 1985)

FAD *Discoaster quinqueramus*—base Zone NN 11—late Miocene (Martini, 1971; Bukry, 1973; Perch-Nielsen, 1985)

LAD *Discoaster calcaris*—upper Zone NN 10—late Miocene (Martini, 1971; Perch-Nielsen, 1985)

LAD *Discoaster prepentaradiatus*—upper Zone NN 10—late Miocene (Bukry, 1973; Perch-Nielsen, 1985)

LAD **Discoaster hamatus*—top Zone NN 9—late Miocene (Martini, 1971; Bukry, 1973; Perch-Nielsen, 1985)

FAD *Discoaster prepentaradiatus*—Zone NN 9—late Miocene (Bukry, 1973; Perch-Nielsen, 1985)

FAD *Discoaster neohamatus*—sporadic occurrence in lower Zone NN 9, consistent from upper Zone NN 9—late Miocene (Martini, 1971; Bukry, 1973; Perch-Nielsen, 1985)

FAD *Discoaster pentaradiatus*—lower Zone NN 9, but possibly as high as Zone NN 11—late Miocene (Martini, 1971; Perch-Nielsen, 1985)

FAD **Discoaster hamatus*—base Zone NN 9—late Miocene (Martini, 1971; Bukry, 1973; Perch-Nielsen, 1985)

FAD *Discoaster calcaris*—within Zone NN 8—middle to late Miocene (Martini, 1971; Perch-Nielsen, 1985)

FAD *Discoaster brouweri*—upper Zone NN 5, possibly Zone NN 8—middle Miocene (Martini, 1971)

FAD *Discoaster moorei*—within Zone NN 5—middle Miocene (Bukry, 1973; Perch-Nielsen, 1985)

FAD *Discoaster variabilis*—sporadic occurrence within Zone NN 4—early Miocene, consistent from base of Zone NN 5—middle Miocene (Martini, 1971; Bukry, 1973; Perch-Nielsen, 1985)

The use and interpretation of stratigraphic ranges of some taxa require additional explanation. *Discoaster variabilis* has been reported to occur sporadically in Zone NN 4 and then to occur consistently from Zone NN 5 up to Zone NN 16. Because calcareous nannofossils, particularly the discoasters, are never very common in the Enewetak sediments, we assumed that any occurrence of *D. variabilis* in Zone NN 4 was unlikely to be observed. Therefore, when this species is present in Enewetak samples, we assumed that the sample was no lower than Zone NN 5. We do not consider the FAD of *D. brouweri* to be a very reliable datum because it appears to occur sporadically below Zone NN 11. For example, Martini (1971) indicated that the base of this species was in the top of Zone NN 5, while Bukry (1973), Gartner (1977b), and Perch-Nielsen (1985) placed its base no lower than Zone NN 8. The FAD of *Discoaster pentaradiatus* also is somewhat questionable. Martini (1971) and Perch-Nielsen (1985) indicated a FAD for this species within lower Zone NN 9, Gartner (1977a) placed it in lower Zone NN 10, and Bukry (1973) placed it in lower Zone NN 11. We find a Zone NN 9 position for the FAD of *D. pentaradiatus* to be consistent with other species' ranges observed within the PEACE cores.

Berggren and others (1985) (fig. 2) placed the Miocene-Pliocene boundary in the lower part of Zone NN 12 at the base of the Gilbert Chron (above the LAD of *D. quinqueramus*). The closest calcareous nannofossil event in our material to the Miocene-Pliocene boundary is the LAD of *D. quinqueramus*, which Berggren and others (1985) placed at 5.6 Ma. For this paper, because of the poor and sporadic occurrences of fossil datums, we consider sediments above the LAD of *Discoaster quinqueramus* (Zone NN 12 or younger) to be Pliocene.

Reticulofenestra pseudoumbilica is never an easy species to identify with a light microscope, and we have confined usage of this species to larger specimens of the genus *Reticulofenestra* having a well-developed central area. *Sphenolithus abies* and *S. neoabies*, the two youngest representatives of this genus, both become extinct at or near the top of Zone NN 15. The genus *Sphenolithus* is more prevalent in the PEACE samples than *R. pseudoumbilica*, and so the LAD of *Sphenolithus* often was used to approximate the top of Zone NN 15.

Species of the genus *Gephyrocapsa* are virtually impossible to differentiate without the use of a scanning electron microscope (SEM). For this study, we divided all the species in this genus into *Gephyrocapsa* large species and *Gephyrocapsa* small species. *Gephyrocapsa oceanica* and *G. caribbeanica* are grouped together as *Gephyrocapsa* large species because we cannot consistently distinguish between these two species in our Enewetak material. Another reason for combining these two species is the continued disagreement about the amount of variation within each of these species and about their actual stratigraphic ranges. Berggren and others (1985) placed the FAD of *Gephyrocapsa caribbeanica* at 1.74 Ma and the FAD of *Gephyrocapsa oceanica* at 1.68 Ma, both near the Pliocene-Pleistocene boundary at 1.6 Ma and above the base of Zone NN 19 at 1.9 Ma. Rio (1982) also placed the FAD of *G. oceanica* near the Pliocene-Pleistocene boundary. Okada and Bukry (1980), however, placed the FAD of *G. oceanica* much higher in the Pleistocene (mid-Zone NN 19). We follow the usage of Berggren and others (1985) and place the FAD of *Gephyrocapsa* large species near the base of Zone NN 19.

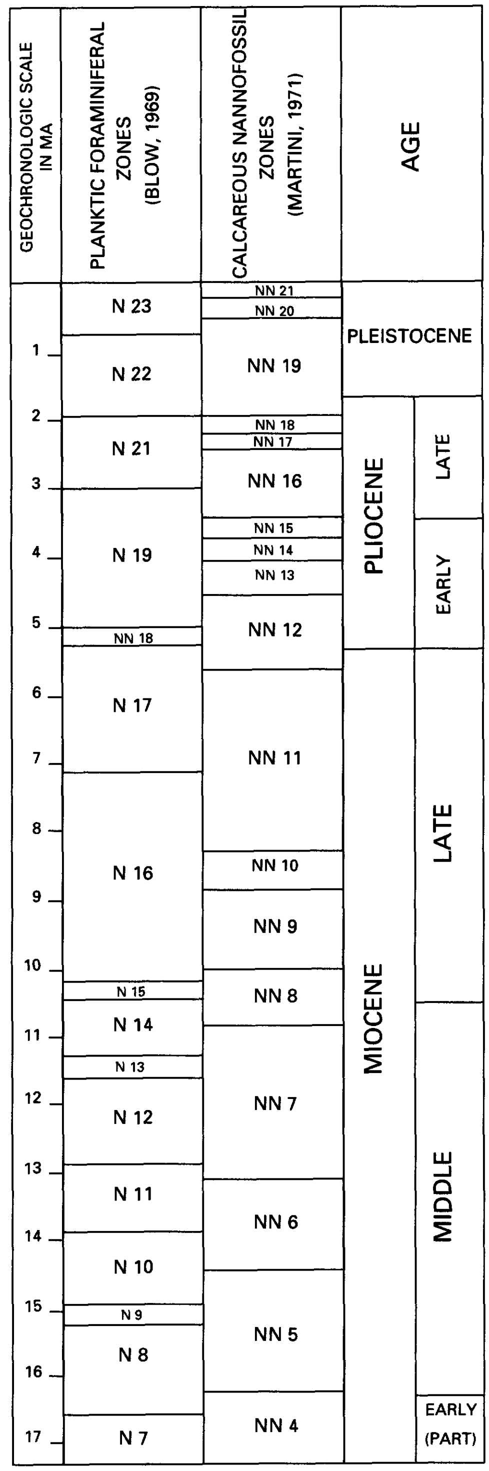


FIGURE 2.—Correlation of planktic foraminiferal and calcareous nannofossil zones to epochs, based on Berggren and others, 1985.

Although large species of *Gephyrocapsa* are known only from the Pleistocene, sporadic occurrences of small species of the genus *Gephyrocapsa* have been reported well into the Pliocene in well-preserved pelagic sequences (Rio, 1982; Perch-Nielsen, 1985; Berggren and others, 1985; Driever, 1988). A recent study of calcareous nannofossils in Panama by Bybell (unpub. data, 1990) indicates that the FAD of *Gephyrocapsa* small species may occur in upper Zone NN 16 or lower Zone NN 17 in Panama. In the Enewetak samples, however, the FAD of *Gephyrocapsa* small species often is only slightly below or at the same depth as the FAD of *Gephyrocapsa* large species (near the base of Zone NN 19). The absence of *Gephyrocapsa* small species well below the FAD of *Gephyrocapsa* large species may indicate that upper Zone NN 16, Zone NN 17, and Zone NN 18 are missing at Enewetak.

The LAD of *Discoaster brouweri* at 1.9 Ma (Berggren and others, 1985) marks the top of Zone NN 18, and this horizon often is used to approximate the Pliocene-Pleistocene boundary, which Berggren and others (1985) placed at 1.6 Ma. However, *D. brouweri* occurs only sporadically in Enewetak material and was not a useful horizon here. The LAD of *Calcidiscus macintyrei*, a more commonly occurring species at Enewetak, is at 1.45 Ma (within the early Pleistocene, according to Berggren and others, 1985). For this paper, if *Gephyrocapsa* large species (FAD at 1.74 Ma or 1.68 Ma) and *Calcidiscus macintyrei* (LAD at 1.45 Ma) are both present in a sample, the age is assumed to be lower Zone NN 19 (Pliocene). If a sample is above the LAD of *C. macintyrei*, the age is assumed to be upper Zone NN 19 (Pleistocene).

Pseudoemiliania lacunosa (its LAD marks the top of Zone NN 19) is rarely observed in most of the PEACE samples (probably due to the difficulty in identifying this species when it is poorly preserved), and *Emiliania huxleyi* (whose FAD marks the base of Zone NN 21) was never observed. This absence made effectively separating Zone NN 19 from Zone NN 20 difficult and separating Zone NN 20 from Zone NN 21 on the basis of calcareous nannofossils impossible.

PLANKTIC FORAMINIFERS

LAD *Globigerinoides obliquus*—base Zone N 22—Pliocene (Blow, 1969; Kennett and Srinivasan, 1983)
LAD *Globoquadrina altispira*—base N 21—Pliocene (Blow, 1969)
LAD *Sphaeroidinellopsis* spp.—base N 21—Pliocene (Blow, 1969)
LAD *Globigerina nepenthes*—N 19—Pliocene (Blow, 1969)
FAD *Globorotalia ungulata*—base N 19—Pliocene (Blow, 1969)
FAD *Globigerinoides conglobatus*—N 18—Pliocene (Blow, 1969; Kennett and Srinivasan, 1983)
LAD *Globoquadrina dehiscens*—N 18—Pliocene (Kennett and Srinivasan, 1983)
FAD *Pulleniatina primalis*—N 17—late Miocene (Blow, 1969)
FAD **Neogloboquadrina acostaensis*—base N 16—late Miocene (Blow, 1969)
FAD **Globigerina nepenthes*—base N 14—middle Miocene (Blow, 1969)
FAD *Globorotalia menardii*—top N 13—middle Miocene (Blow, 1969)
LAD *Globigerinoides subquadratus*—top N 13—middle Miocene (Blow, 1969)
FAD **Orbulina* spp.—base N 9—middle Miocene (Blow, 1969)

Globoquadrina altispira, *Sphaeroidinellopsis* spp., *Globigerinoides conglobatus*, and *Globoquadrina dehiscens* were useful in delineating the Pliocene interval of the Enewetak samples. Most compilations (for example, Blow, 1969; Kennett and Srinivasan, 1983; Bolli and Saunders, 1985) show that the LAD's of *Sphaeroidinellopsis* spp. and *Globoquadrina altispira* fall near the base of Zone N 21 at a Pliocene level dated at about 2.9 Ma (Dowsett, 1989). The zonation outlined by Blow (1969) included Zone N 20 in the Pliocene. Subsequent work has shown that Zone N 20 cannot be identified with confidence because the taxon whose first occurrence defines the base of Zone N 20 (*Neogloboquadrina acostaensis pseudopima* (Blow)) is not recognized by most workers. As a result, Zone N 20 either has not been used or it has been combined with Zone N 19 (for example, Berggren and others, 1985; Kennett and Srinivasan, 1983). The first occurrence of *Globorotalia tosaensis* Takayanagi and Saito s.l. defines the base of Zone N 21. However, *G. tosaensis* has a restricted geographic distribution and has limited use for routine identification of Zone N 21. Thus, we use the last occurrences of *Globoquadrina altispira* and *Sphaeroidinellopsis* spp. to approximate the base of Zone N 21.

The base of the Pliocene is now considered to coincide with the base of Zone N 18 (Berggren and others, 1985). We approximated the base of the Pliocene with the last occurrence of *Globoquadrina dehiscens* (LAD at the top of Zone N 18) and the first occurrence of *Globigerinoides conglobatus* (FAD at base of Zone N 18) (Kennett and Srinivasan, 1983; Bolli and Saunders, 1985). We consider that this convention is adequate for this study because the duration of Zone N 18 is very short (about 100,000 yr).

MICROFOSSIL OCCURRENCES AND ZONE ASSIGNMENTS FOR INDIVIDUAL BOREHOLES

The stratigraphic significance of calcareous nannofossil and planktic foraminiferal occurrences and their relationship to the local benthic zonation are discussed by individual fossil group for each core, and the discussion of each core begins with the deepest sediments at the bottom of each core and ends with the shallowest sediments at the top of each core. Therefore, the first appearance of a species or FAD within an individual core, as described in this paper, is necessarily deeper in a core than its last appearance or LAD.

OOR–17

CALCAREOUS NANNOFOSSILS

Calcareous nannofossil occurrences in samples from borehole OOR–17 are listed on figure 3. The lower part of the core from 1,068 ft to 948 ft is barren of calcareous nannofossils, and the interval from 941 ft to 825 ft does not contain diagnostic calcareous nannofossils. The presence of *Discoaster pentaradiatus* at 813 ft indicates an assignment no older than Zone NN 9 or a late Miocene age. The occurrence of *Discoaster prepentaradiatus* at 777 ft indicates assignment to either Zone NN 9 or NN 10 (late Miocene). Therefore, the interval from 813 ft to 777 ft is within Zones NN 9 and (or) NN 10. The occurrence of *D. pentaradiatus* below the occurrence of *D. prepentaradiatus* (FAD in Zone NN 9) in this core indicates that the FAD of *D. pentaradiatus* is more accurately placed in Zone NN 9 than in Zone NN 11. The last occurrence of the genus *Sphenolithus* at 339 ft is used to approximate the top of Zone NN 15 in the core. Specimens in this sample could be identified only as sphenoliths, and presumably they belong to the species *Sphenolithus abies*. Regardless of the species assignment, the 339-ft level can be no younger than Zone NN 15 or mid-Pliocene, on the basis of last occurrence of this genus. The occurrence of *Pseudoemiliania lacunosa* and the absence of the genus *Sphenolithus* at 292 ft indicate that this depth is in Zone NN 16 or younger (late Pliocene). The first occurrence of large specimens of *Gephyrocapsa* at 137 ft indicates that this depth is definitely no older than Zone NN 19 or latest Pliocene to Pleistocene. The FAD of *Gephyrocapsa* small species is at 194 ft, which may indicate that Zone NN 19 extends down to this depth; the stratigraphic placement for the FAD of *Gephyrocapsa* small species is discussed in the Composite Sequence section. The presence of *Pseudoemiliania lacunosa* at 132 ft indicates that this depth is no younger than Zone NN 19.

PLANKTIC FORAMINIFERS

Occurrences of planktic foraminifers in samples from borehole OOR–17 are shown on figure 4. The occurrence of *Orbulina universa*, together with *Globigerinoides subquadratus*, in the sample from 930 ft indicates that the assemblage is within the interval from Zones N 9 to N 13 or the middle Miocene. Samples from 866 ft to 292 ft are difficult to attribute to a zone with any confidence. The presence of *Globigerina nepenthes* in samples at 722 ft and 642 ft indicates placement somewhere in the interval from Zones N 14 to N 19 or the middle Miocene to Pliocene. The occurrence of a form close to *Neogloboquadrina acostaensis* in the sample from 614 ft indicates that this sample is no older than Zone N 16 (late Miocene), but it may be as young as Zone N 19 (Pliocene) because *Globigerina nepenthes* is present. *Pulleniatina primalis* first evolves in the upper part of Zone N 17, and its occurrence in samples from 511 ft and 331 ft indicates that the samples are no older than Zone N 17 or the late Miocene.

The overlap of *Globigerinoides conglobatus* and *Sphaeroidinellopsis* spp. in samples from 292 ft and 270 ft indicates that these assemblages are within Zones N 19 to the lower part of Zone N 21 (Pliocene). Samples from 101 ft and 67 ft, which contain *Globigerinoides tenellus* and red *Globigerina rubescens* (at 67 ft), are within the interval of the Pleistocene Zones N 22 and N 23.

OBZ–4

CALCAREOUS NANNOFOSSILS

Seven samples between 1,543 and 924 ft were examined for calcareous nannofossils, and none of these samples yielded any identifiable species. No additional samples were examined from this core.

PLANKTIC FORAMINIFERS

Occurrences of planktic foraminifers in samples from borehole OBZ–4 are shown on figure 5. The sample at 808 ft from this core contains the planktic foraminifers *Orbulina universa* and *Globigerinoides subquadratus*, which are indicative of middle Miocene Zones N 9 to N 13 (calcareous nannofossil Zones NN 5–NN 7 and within benthic zone lower LL). The other samples examined from this core were barren or yielded extremely poor planktic foraminiferal assemblages.

OAR–2 AND 2A

CALCAREOUS NANNOFOSSILS

Calcareous nannofossil occurrences for boreholes OAR–2 and OAR–2A are listed on figure 6. The interval between 836 ft and 749 ft has no age diagnostic calcareous nannofossils. *Discoaster variabilis*, which occurs at 726 ft, indicates an age assignment no older than Zone

NN 5 or middle Miocene. The occurrence of *Discoaster pentaradiatus* at 663 ft indicates an assignment no older than Zone NN 9 or late Miocene for this depth. *Discoaster berggrenii*, which occurs at 659 ft, restricts this sample to Zone NN 11 (late Miocene). The presence of *Reticulofenestra pseudoumbilica* at 247 ft and *Sphenolithus abies* at 245 ft indicates that these samples are no younger than Zone NN 15 or early Pliocene. The presence of *Pseudoemiliania lacunosa* and *Calcidiscus macintyrei* and the absence of the genus *Sphenolithus* at 141 ft indicate that the age of this sample is between Zone NN 16 and lower Zone NN 19 (late Pliocene). Calcareous nannofossils were not examined in these cores above 141 ft.

PLANKTIC FORAMINIFERS

Planktic foraminiferal taxa recorded in samples from boreholes OAR–2 and OAR–2A are listed on figure 5. The occurrence of *Globigerina nepenthes* or *Globorotalia menardii*, along with *Globoquadrina dehiscens* in assemblages from samples at 760 ft and 726 ft, indicates assignment within the interval from Zone N 14 to Zone N 17 or middle to late Miocene. We did not routinely separate *Globigerinoides extremus* from *G. obliquus* during this study because of the poor preservation and limited populations available. However, good representatives of *Globigerinoides extremus*, which first occurs in Zone N 17, are present in the sample at 569 ft. Thus, the interval from 569 ft up to the first occurrence of *Globigerinoides conglobatus* at 290 ft is no older than Zone N 17, and it may represent Zone N 18 or N 19. The overlap of *Globigerinoides conglobatus* with *Globigerina nepenthes* in the sample at 290 ft indicates placement in Zone N 19 (Pliocene). The presence of *Sphaeroidinellopsis* spp. and *Globoquadrina altispira*, without *Globigerina nepenthes*, in samples from 268 ft and 245 ft indicates that these samples are in the interval of Zone N 19 to the lower part of Zone 21 (Pliocene). Assemblages from the top two samples examined for these cores at 195 ft and 90 ft indicate that the age may be from Zone N 19 to Zone N 23 (Pliocene to Pleistocene).

KBZ–4

CALCAREOUS NANNOFOSSILS

Calcareous nannofossil occurrences for borehole KBZ–4 are listed in figure 3. The bottom portion of this hole between 1,045 and 880 ft cannot be dated by using calcareous nannofossils. The presence of *Discoaster variabilis* at 876 ft indicates an age of probably no older than Zone NN 5 or middle Miocene. This age is confirmed by the presence of both *Discoaster brouweri* (FAD in NN 5 or younger) and *Discoaster moorei* (FAD in Zone NN 5) in the sample at 864 ft.

The next diagnostic species occurs at 777 ft, where *Discoaster hamatus* restricts this depth to Zone NN 9 (late Miocene). The presence of several other discoasters at this depth is consistent with a placement within Zone NN 9: *Discoaster neohamatus*, *Discoaster brouweri*, *Discoaster challengeri*, and a possible *Discoaster bollii*. *Discoaster signus* also occurs at this depth; this species has been reported only from Zones NN 5 and NN 6 (Bukry, 1973; Perch-Nielsen, 1985), but its presence here, along with the other discoasters that definitely indicate a younger age, suggests that *D. signus* has a longer range than previously reported. The presence of *Discoaster quinqueramus* at 756 ft indicates an age of Zone NN 11 (late Miocene). Therefore, the interval between 777 ft and 756 ft is confined to Zones NN 9–11. *Discoaster berggrenii* occurs at 751 ft, and *D. neohamatus* is present at 751 and 746 ft. The highest occurrence of *D. quinqueramus* is at 575 ft, and so the interval from 756 and 575 ft is within Zone NN 11. The next significant horizon is the last occurrence of the genus *Sphenolithus* at 490 ft, whose presence means that this sample is no younger than Zone NN 15. Between 490 ft and 206 ft, this core is essentially barren of calcareous nannofossils, and there are no diagnostic species in the few samples that do contain calcareous nannofossils. At 206 ft is the FAD of *Gephyrocapsa* small species and *Gephyrocapsa* large species; these species indicate an age no older than Zone NN 19. *Pseudoemiliania lacunosa* occurs at 162 ft, and so the interval from 206 to 162 ft is restricted to Zone NN 19. *Calcidiscus macintyrei* last occurs at 187 ft, and so the interval from 206 to 187 ft can be placed in the lowest part of Zone NN 19 (Gartner, 1977b), the latest Pliocene. No diagnostic calcareous nannofossils occur above 162 ft.

This borehole was drilled inside one of the nuclear blast craters, and there is a zone of obvious mixing above 142 ft (see fig. 8). Below 142 ft, there also is evidence of upward piping of sediments; this piping can be recognized by the presence of older macrofossil material near the surface of this core. However, the calcareous nannofossil occurrences in borehole KBZ–4 below 142 ft are consistent with occurrences in the other PEACE boreholes, and we see no evidence for displacement of calcareous nannofossils in these samples. Thus, these data have been incorporated into our evaluation of the Enewetak boreholes.

PLANKTIC FORAMINIFERS

Planktic foraminifers recorded in samples from borehole KBZ–4 are listed on figure 5. The occurrence of

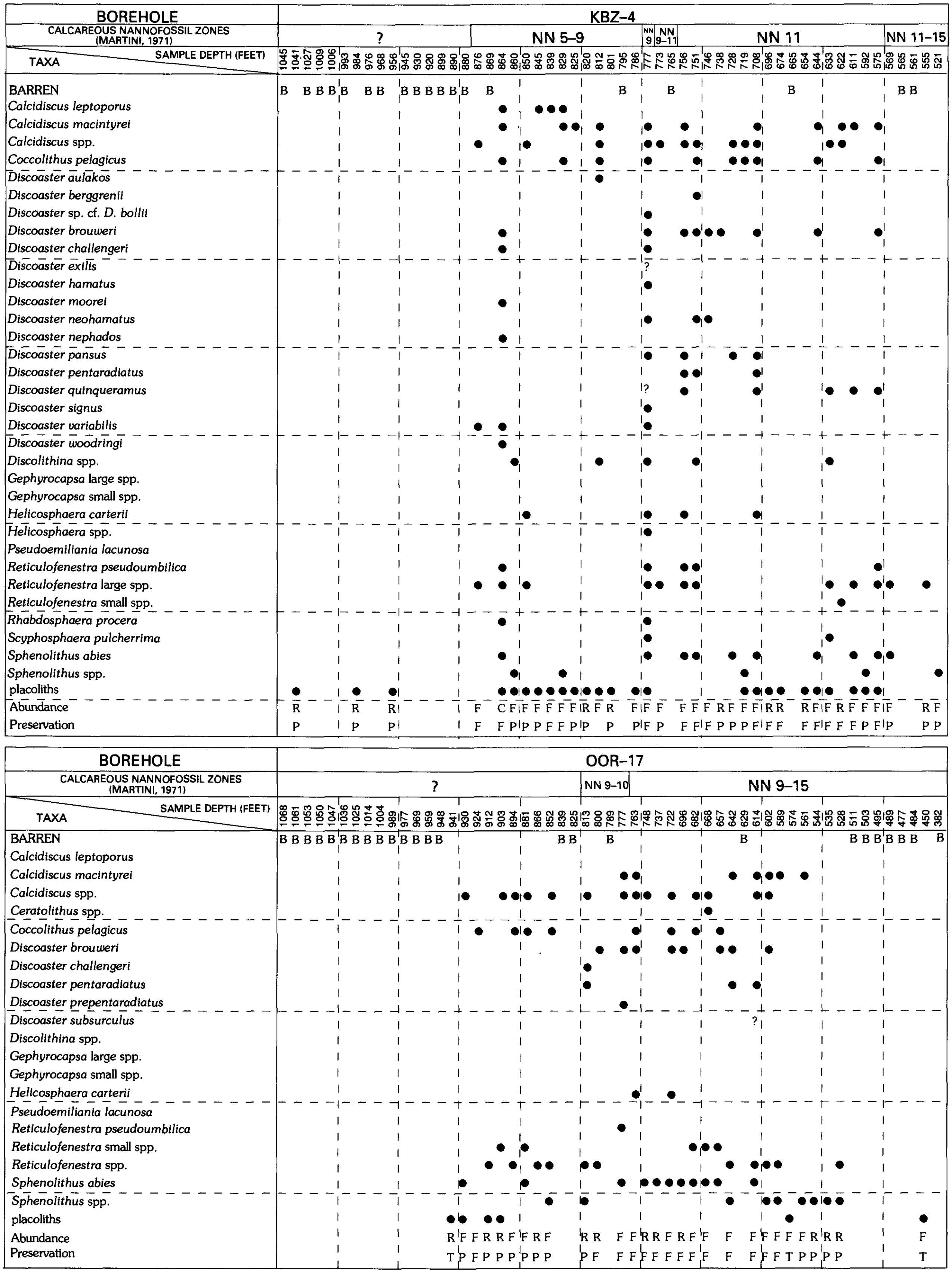
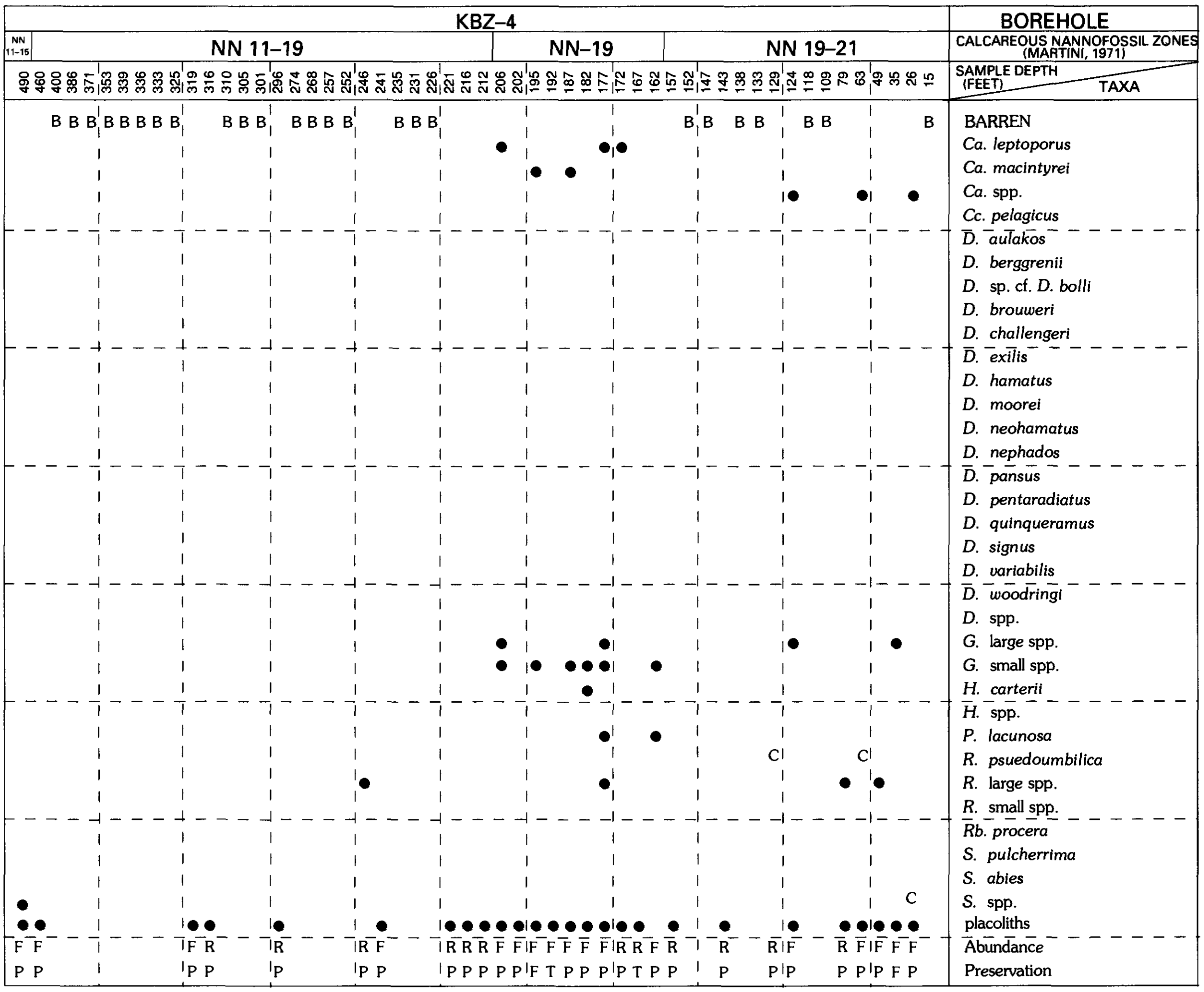
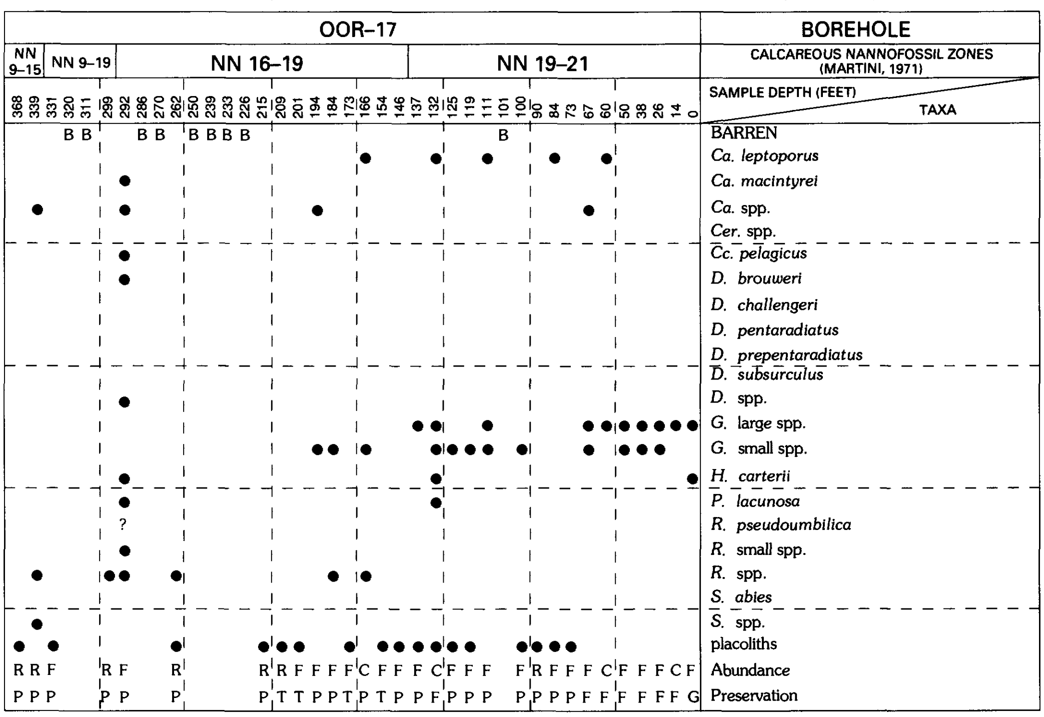


FIGURE 3.—Calcareous nannofossil occurrences in boreholes KBZ-4 and OOR-17. C on the chart indicates probable contamination, abundance, C=common or 1–10 specimens per field of view at 500 × magnification, F=frequent or 1 specimen per 1–10 fields of G=good preservation, F=fair preservation, P=poor preservation, and T=terrible preservation.





a question mark indicates a possible occurrence, and B indicates a sample barren of calcareous nannofossils. For view at 500 × magnification, and R=rare or 1 specimen per 10–100 fields of view at 500 × magnification. For preservation,

BOREHOLE	SAMPLE DEPTH IN CORE (FEET)	*Globigerina nepenthes*	*G. rubescens*	*G. woodi*	*Globigerinella aequilateralis*	*Globigerinita glutinata*	*Globigerinoides conglobatus*	*G. obliquus*	*G. ruber*	*G. sacculifer*	*G. subquadratus*	*G. tenellus*	*Globoquadrina altispira*	*G. dehiscens*	*Globorotalia menardii*	*G. miocenica*	*G. ungulata*	*Neogloboquadrina acostaensis*	*N. humerosa*	*Orbulina universa*	*Pulleniatina obliquiloculata*	*P. primalis*	*Sphaeroidinellopsis spp.*	FORAMINIFERAL ZONES (BLOW, 1969)
KAR-1	203					●			●	●													?	
	240							●		●														
	283							●		●													●	N 19–N 21
	552	●						●														?	●	N 22–N 23
	557	●						●		●							●						●	
	591	?						●		●			●											
	604							●		●			●										●	
	866																				C			
	887							●		●				●									●	
	893							●						●									●	
OOR-17	67		●				●		●	●		●												N 19
	101				●		●		●	●		●												
	239																●						?	
	270			●	●	●	●	●	●	●			●		●	?			●			●	●	N1 9–N 21
	292			●		●	●	●	●	●												●	●	
	331							●		●			●		●							●	●	N 17–N 21
	511							●		●												●		
	574	●		●				●	?	●			●							●			●	N 16–N 19
	589	●						●		●			●										●	
	614	●						●		●			●			?		?					●	
	642	●						●		●			●										●	N 14–N 19
	722	●						●		●			?										●	
	866							●		●										●			●	
	930							●		●	●									●				N 9–N 13

FIGURE 4.—Planktic foraminiferal occurrences in boreholes KAR-1 and OOR-17. C indicates probable contamination, and a question mark indicates a possible occurrence.

Globigerinoides subquadratus in the sample from 864 ft indicates that this sample is within or below Zone N 13 or middle Miocene or older. The occurrence of *Globoquadrina dehiscens* with *Globorotalia menardii* at 777 ft indicates that this sample is within the interval from Zone N 14 to Zone N 17 or middle to late Miocene. Our interpretation excludes the unlikely possibility that this sample represents the short basal Pliocene Zone N 18.

BOREHOLE	SAMPLE DEPTH IN CORE (FEET)	*Globigerina decoraperta*	*G. nepenthes*	*G. woodi*	*Globigerinita glutinata*	*Globigerinoides conglobatus*	*G. obliquus* (s.l.)	*G. ruber*	*G. sacculifer*	*G. subquadratus*	*Globoquadrina altispira*	*G. dehiscens*	*Globorotalia menardii*	*G. miocenica*	*G. plesiotumida*	*G. ungulata*	*Orbulina universa*	*Pulleniatina obliquiloculata*	*P. primalis*	*Sphaeroidinellopsis* spp.	FORAMINIFERAL ZONES (BLOW, 1969)
OAR–2 and 2A	90						?	●	●							●					
	195						●	●	●							●				?	
	245				●	?	●		●		●				●	●				●	N 19 – N 21
	268						●		●		●				?				●	●	
	290		●			●	●		●		●		●	?			●		●	●	N 19
	498		●				●		●		●	?	?				●			●	N 17 – N 19
	555		●				●		●		●									●	
	569		●				●		●		●						●			●	
	579						●		●		●										
	659		●				●		●		●									●	
	726	●	?		●		●		●		●	●	●							●	N 14 – N 17
	760	●	●				●		●		●	●					●			●	
KBZ–4	226	●	●			●	●	●	●		●			?	?		●		●	●	N 19
	333																	●			
	555		●				●		●		●									●	
	561		●				●													●	
	592	●	●				●		●		●		●	?						●	
	674		●				●		●											●	
	777	●		?	●		●		●		●	●	●							●	N 14 – N 17
	864			●	●		●		●	●	●									●	↓ N 13
OBZ–4	808			●			●		●	●	●						●			●	N 9 – N 13
XEN–3	245						●	●	●				?							?	
	262						●	●	●						●	●				●	N 18 – N 21

FIGURE 5.—Planktic foraminiferal occurrences in boreholes OAR–2 and 2A, KBZ–4, OBZ–4, and XEN–3. A question mark indicates a possible occurrence, and a down arrow indicates that the zonal assignment may be older but not younger.

The isolated occurrence of *Pulleniatina obliquiloculata* in the sample from 333 ft appears to be in situ because it is poorly preserved and encrusted with secondary calcite overgrowths, as are several other unidentified specimens recovered from the sample. This condition matches the recrystallized nature of the sediments in this interval. Because *Pulleniatina obliquiloculata* first occurs in Zone N 19, the sample at 333 and the sample at 226 ft, which contains *Globigerina nepenthes* and *Globigerinoides conglobatus*, are assigned to the Pliocene Zone N

BOREHOLE	OAR–2 and 2A																															
CALCAREOUS NANNOFOSSIL ZONES (MARTINI, 1971)	?								NN 5–11			NN 9–11	NN 11	NN 11–15											NN11–19							
TAXA / SAMPLE DEPTH (FEET)	836	828	815	800	791	773	760	749	726	716	690	663	659	623	612	606	596	587	579	569	474	432	247	245	235	212	205	195	188	171	157	141
BARREN	B		B					B			B			B	B			B			B				B			B			B	
Calcidiscus leptoporus																								●								
Calcidiscus macintyrei				●	●								●										●	●								●
Calcidiscus spp.				●	●		●		●			●	●				●		●	●									●			
Coccolithus eopelagicus		●																														
Coccolithus pelagicus				●		●			●			●																				
Discoaster berggrenii													●																			
Discoaster brouweri		?										●																				
Discoaster deflandrei							C																									
Discoaster pansus				●																												
Discoaster pentaradiatus												●																				
Discoaster variabilis		?							●			●																				
Helicosphaera carterii												●																				
Pseudoemiliania lacunosa																																●
Reticulofenestra spp.				●	●				●							●	●		●	●		●	●	●		●	●					●
Reticulofenestra pseudoumbilica							?																●									
Reticulofenestra umbilica										C																						
Rhabdosphaera spp.					●																											
Scyphosphaera intermedia												●																				
Sphenolithus abies		●																						●								
Sphenolithus spp.				●	●	●	●		●			●	●						●	●												
placoliths				●	●		●																							●		●
Abundance		F		F	F	R	F		F	R		F	F			R	F		F	F		R	F	F		F	R		R	R		F
Preservation		P		F	P	P	P		F	P		F	P			P	P		F	F		P	F	P		P	P		P	P		P

FIGURE 6.—Calcareous nannofossil occurrences in boreholes OAR–2 and 2A. See figure 3 for an explanation of abundance, preservation, and symbols used on the figure.

19. Assemblages found between 777 ft and 333 ft can be assigned only to the broad interval from Zone N 14 to Zone N 19 or late middle Miocene to Pliocene.

KAR–1

CALCAREOUS NANNOFOSSILS

Occurrences of calcareous nannofossils from borehole KAR–1 are shown on figure 7. Much of the lower part of KAR–1 between 1,146 ft and 870 ft is barren of calcareous nannofossils. However, the presence of the species *Discoaster brouweri*, along with *D. variabilis*, at 927 ft indicates that this level in the core is no older than NN 5 or middle Miocene. The presence of *Discoaster pentaradiatus*, which indicates an age no older than Zone NN 9, and *Discoaster calcaris*, which indicates an age of Zones NN 8–10, at 852 ft constrains this sample within Zone NN 9 or NN 10 (late Miocene). The occurrence of the species *Discoaster moorei* at 817 ft is anomalous; this species is reported to occur only in Zones NN 5–7 (Perch-Nielsen, 1985). Its presence at this depth indicates either reworking or the extension of this species' range into Zone NN 9. *Discoaster quinqueramus*, which is restricted to Zone NN 11, occurs at 741 ft; *Discoaster berggrenii*, which also is confined to Zone NN 11, occurs at 626 ft. Thus, the interval between 741 ft and 626 ft is placed in Zone NN 11 or the late Miocene. *Sphenolithus abies*, which has its LAD near the top of Zone NN 15, last occurs at 448 ft, and so the age at this depth is no younger than Zone NN 15 or Pliocene. One *Sphenolithus* specimen found in the sample at 197 ft is assumed to be due to contamination because not only is it out of place stratigraphically, but also it was the only identifiable calcareous nannofossil in the entire sample. Large specimens of the genus *Gephyrocapsa* first occur at 118 ft; this occurrence indicates that this sample is no older than Zone NN 19, although *Gephyrocapsa* small species first occurs at 152 ft. Occurrences of *Pseudoemiliania lacunosa* at 118 ft, 100 ft, and 95 ft indicate that these samples are no younger than Zone NN 19. There are questionable occurrences of *Calcidiscus macintyrei* at

100 and 70 ft. These two occurrences have been attributed to contamination, probably as reworking from below, because correlative material elsewhere at Enewetak has calcareous nannofossil, as well as radiocarbon and uranium-series, dates that place these sediments within the Pleistocene, thus above the last occurrence of *C. macintyrei* (see Composite Sequence and Radiometric Dating sections). Scattered throughout this core are several other examples of obvious contamination due to reworking. These are marked with a C in the occurrence chart on figure 7 and include a few Eocene forms and two occurrences of *Discoaster deflandrei.*

PLANKTIC FORAMINIFERS

Planktic foraminifers identified from KAR–1 are shown on figure 4. Assemblages from the lower part of the core are not particularly diagnostic, although the bottom two samples at 893 ft and 887 ft are Miocene, on the basis of the presence of *Globoquadrina dehiscens.*

Several assemblages from the upper part of the borehole are diagnostic of the Pliocene. For example, *Globorotalia ungulata* occurs with *Globigerina nepenthes* in the sample from 557 ft. *Globigerina nepenthes* also occurs in the sample from 552 ft, and *Sphaeroidinellopsis* occurs in the sample from 283 ft. Thus, the samples from 557 ft and 552 ft are assigned to the Pliocene Zone N 19, and the sample from 283 ft is within the Pliocene interval of Zone N 19 to Zone N 21. One relatively well-preserved specimen of *Pulleniatina obliquiloculata* was found in a split from the sample at 866 ft. The remainder of this sample was examined extensively, and the only other planktic foraminifer found was a poorly preserved "*Globorotalia.*" Thus, we consider the specimen of *Pulleniatina obliquiloculata* from this sample to represent sampling or laboratory contamination.

XEN–3

CALCAREOUS NANNOFOSSILS

Calcareous nannofossil occurrences for borehole XEN–3 are listed in figure 7. There are no diagnostic calcareous nannofossils in the lower part of this borehole from 297 ft to 250 ft. The presence of *Gephyrocapsa* large species at 248 ft indicates an age no older than Zone NN 19. *Calcidiscus macintyrei*, which does not occur above the lower part of Zone NN 19, is found up to 148 ft, and so the interval between 248 ft and 148 ft is within lower Zone NN 19 (latest Pliocene in age). The interval between 144 ft and the top of the core, which is above the last occurrence of *C. macintyrei*, is most probably within the Pleistocene on the basis of calcareous nannofossils, but it cannot be further subdivided due to the absence of other diagnostic Pleistocene species.

PLANKTIC FORAMINIFERS

Planktic foraminifers identified in core XEN–3 are listed in figure 5. The sample from 262 ft, which contains *Globorotalia plesiotumida*, *Sphaeroidinellopsis*, and *Globorotalia ungulata*, is Pliocene in age. The specimen questionably assigned to *Sphaeroidinellopsis* in the sample at 245 ft is too poorly preserved to be used to assign a Pliocene age to that sample.

E–1

One core sample (2,003–2,028 ft) was examined from the E–1 borehole. The sample contains the calcareous nannofossils *Coccolithus eopelagicus*, *C. pelagicus*, *Pedinocyclus larvalis*, *Reticulofenestra floridana*, and *Sphenolithus* sp., most of which occur in both the Oligocene and Miocene. However, *P. larvalis* does not appear to occur later than late Oligocene (Perch-Nielsen, 1985). Bybell (unpub. data, 1982) indicates that its occurrence is as high as either Zone NP 24 or NP 25. The E–1 sample also contains the planktic foraminifers *Globorotalia kugleri*, *Globigerina ciperoensis*, *G. bulloides*, *Streptochilus* sp., and a questionable *G. angulisuturalis*. The presence of *G. kugleri* may place the sample either in the latest Oligocene or earliest Miocene (Bolli and Saunders, 1985) or within the earliest Miocene (Berggren and others, 1985). If *Pedinocyclus larvalis* does not occur later than the Oligocene, it indicates that this sample is confined to the late Oligocene. However, neither *Dictyococcites bisectus*, *Helicosphaera recta*, nor *Zygrhablithus bijugatus* (species that do not extend above the late Oligocene) is present in this sample. Therefore, the E–1 sample has been dated as either latest Oligocene or earliest Miocene.

COMPOSITE SEQUENCE

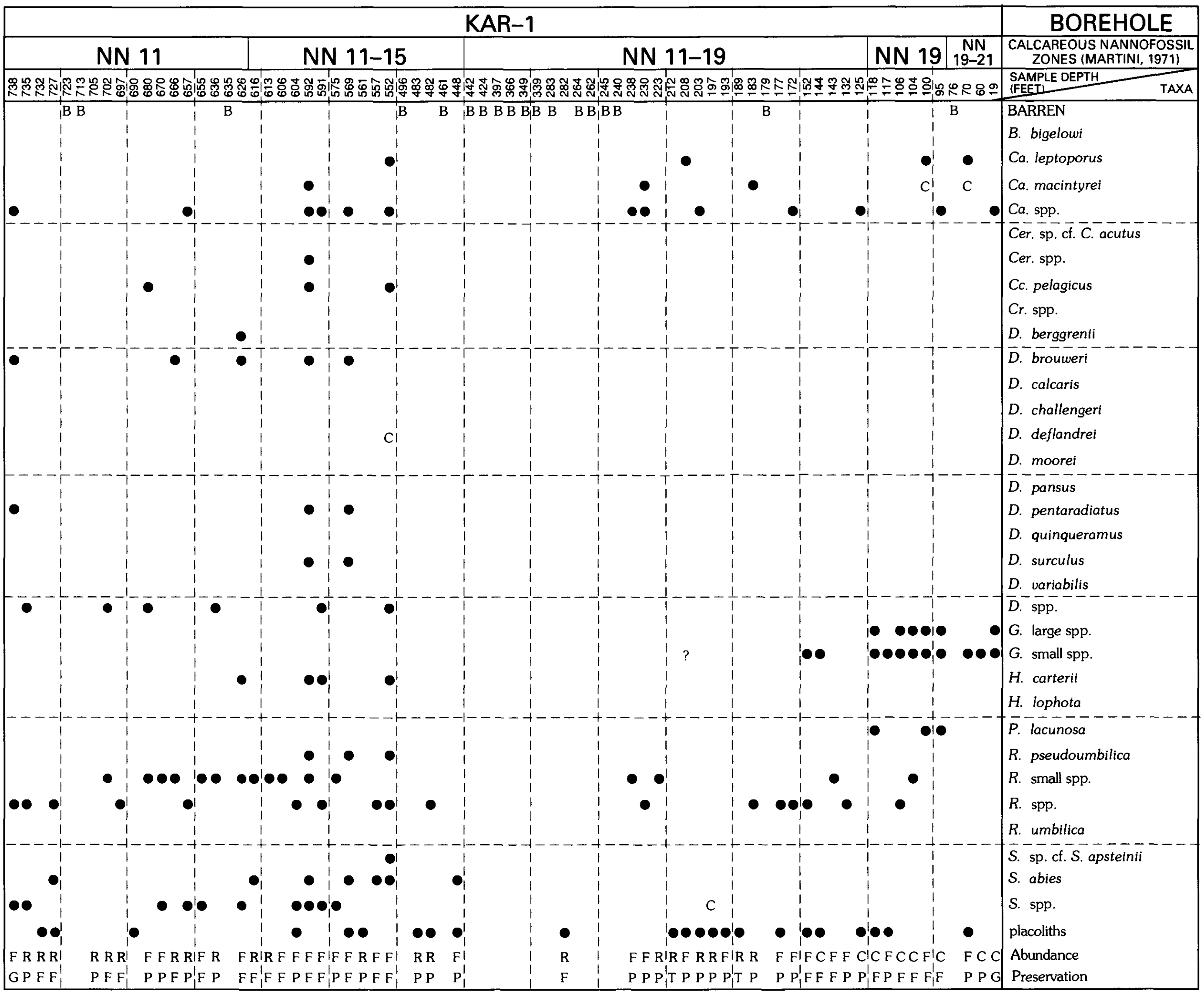
Once individual boreholes were dated as closely as possible by using calcareous nannofossils and planktic foraminifers, the data for each borehole were plotted against the local benthic zones of Cronin and others (1986), as modified by Cronin (written commun., 1990) (fig. 8). Cronin (written commun., 1990) gave each of the zones and subzones ostracode faunal names. The following is a list of each new ostracode zone and its corresponding old alphabetic designation from Cronin and others (1986):

BOREHOLE	KAR-1																											
CALCAREOUS NANNOFOSSIL ZONES (MARTINI, 1971)	?																			NN 5–10								
TAXA / SAMPLE DEPTH (FEET)	1146	1136	1117	1105	1084	1073	1049	1021	1004	994	991	980	975	957	953	949	944	936	933	927	924	920	913	907	905	893	890	887
BARREN	B	B	B	B	B	B	B	B	B	B		B	B	B	B	B	B	B			B	B		B		B	B	B
Braarudosphaera bigelowi																												
Calcidiscus leptoporus																												
Calcidiscus macintyrei																				●								
Calcidiscus spp.																												
Ceratolithus sp. cf. *C. acutus*																												
Ceratolithus spp.																												
Coccolithus pelagicus																							●					
Cruciplacolithus spp.																												
Discoaster berggrenii																												
Discoaster brouweri																				●								
Discoaster calcaris																												
Discoaster challengeri																												
Discoaster deflandrei																												
Discoaster moorei																												
Discoaster pansus																												
Discoaster pentaradiatus																												
Discoaster quinqueramus																												
Discoaster surculus																												
Discoaster variabilis																				●								
Discoaster spp.																				●								
Gephyrocapsa large spp.																												
Gephyrocapsa small spp.																												
Helicosphaera carterii																				●								
Helicosphaera lophota																												
Pseudoemiliania lacunosa																												
Reticulofenestra pseudoumbilica																									●			
Reticulofenestra small spp.																												
Reticulofenestra spp.																				●			●					
Reticulofenestra umbilica																							C					
Scyphosphaera sp. cf. *S. apsteinii*																												
Sphenolithus abies																									●			
Sphenolithus spp.																												
placoliths											●								●						●			
Abundance											R								R	F			R		F			
Preservation											T								P	F			F		P			

BOREHOLE	KAR-1 (continued)																											
CALCAREOUS NANNOFOSSIL ZONES (MARTINI, 1971)						NN 9–10	NN 9–11																					NN 11
TAXA / SAMPLE DEPTH (FEET)	881	873	870	866	859	852	847	840	834	829	825	822	817	814	808	800	798	795	788	783	781	772	769	763	761	754	747	741
BARREN		B	B								B						B			B	B	B	B	B				
Braarudosphaera bigelowi						●																				●		
Calcidiscus leptoporus														●														
Calcidiscus macintyrei						●								●														
Calcidiscus spp.	●																	●	●							●		●
Ceratolithus sp. cf. *C. acutus*													●															
Ceratolithus spp.																												
Coccolithus pelagicus						●			●				●	●														●
Cruciplacolithus spp.									●																			●
Discoaster berggrenii																												
Discoaster brouweri						●							●	●					●							●	●	●
Discoaster calcaris						●																						
Discoaster challengeri						●		●						●													●	
Discoaster deflandrei																			C									
Discoaster moorei													●															
Discoaster pansus													●	●					●								●	●
Discoaster pentaradiatus						●																				●		
Discoaster quinqueramus																												●
Discoaster surculus																												
Discoaster variabilis						●						●		●	●													
Discoaster spp.										●				●					●							●		●
Gephyrocapsa large spp.																												
Gephyrocapsa small spp.																												
Helicosphaera carterii										●			●															
Helicosphaera lophota													C															
Pseudoemiliania lacunosa																												
Reticulofenestra pseudoumbilica	●					●				●			●	●					●									
Reticulofenestra small spp.																										●		
Reticulofenestra spp.					●							●	●	●														
Reticulofenestra umbilica																												
Scyphosphaera sp. cf. *S. apsteinii*																												
Sphenolithus abies	●													●														●
Sphenolithus spp.				●		●	●		●				●		●	●			●						●			
placoliths				●			●		●																		●	●
Abundance	F			R	R	F	F	R	F	F		F	F	F	R	R		R	F						R	R	F	F
Preservation	F			P	P	G	P	F	F	F		P	F	F	F	F		P	F						P	G	F	F

BOREHOLE	XEN-3																											
CALCAREOUS NANNOFOSSIL ZONES (MARTINI, 1971)	?														NN 19													
TAXA / SAMPLE DEPTH (FEET)	297	296	293	292	285	280	276	271	266	262	259	255	251	250	248	245	241	237	234	229	226	219	213	207	204	198	196	193
BARREN					B															B								
Calcidiscus leptoporus		●	●						●						●	●			●		●	●						
Calcidiscus macintyrei												●		●														
Calcidiscus spp.	●			●									●	●														
Coccolithus pelagicus															●													
Discolithina spp.																												
Gephyrocapsa large spp.															●						●							
Gephyrocapsa small spp.															●	●												
Helicosphaera carterii															●													
Pseudoemiliania lacunosa															?													
Reticulofenestra large spp.						●	●		●			●		●	●	●												
Reticulofenestra small spp.		●	●							●																		
placoliths	●			●				●	●	●	●	●	●	●	●	●	●	●	●		●	●	●	●	●	●	●	●
Abundance	F	F	R	F		R	R	F	F	F	R	F	F	F	F	C	F	F	F		R	R	F	F	F	F	R	F
Preservation	P	P	P	P		P	P	P	P	P	T	P	F	F	F	P	P	T	P		T	P	T	P	T	P	P	T

BOREHOLE	XEN-3 (continued)																											
CALCAREOUS NANNOFOSSIL ZONES (MARTINI, 1971)															NN 19–21													
TAXA / SAMPLE DEPTH (FEET)	190	185	183	179	175	172	171	167	164	159	157	155	149	148	144	141	137	134	130	126	124	120	118	114	113	111	110	107
BARREN																												
Calcidiscus leptoporus				●	●	●	●	●			●	●	●	●		●	●		●		●	●	●		●	●	●	●
Calcidiscus macintyrei				●				●				●		●														
Calcidiscus spp.																		●		●		●						
Coccolithus pelagicus																												
Discolithina spp.																												
Gephyrocapsa large spp.							●	●	●	●		●	●	●														
Gephyrocapsa small spp.		●		●	●		●	●	●	●	●	●	●	●	●		●		●	●	●	●	●	●	●	●	●	●
Helicosphaera carterii																												
Pseudoemiliania lacunosa																												
Reticulofenestra large spp.					●							●				●												
Reticulofenestra small spp.																												
placoliths	●		●	●	●					●					●		●	●	●	●	●			●	●	●	●	●
Abundance	R	F	R	F	R	R	F	C	F	F	R	C	F	F	R	F	F	F	F	F	F	F	F	F	F	F	F	F
Preservation	T	P	P	P	F	P	F	F	P	P	P	F	P	P	P	P	P	P	P	P	P	P	P	P	P	F	P	P



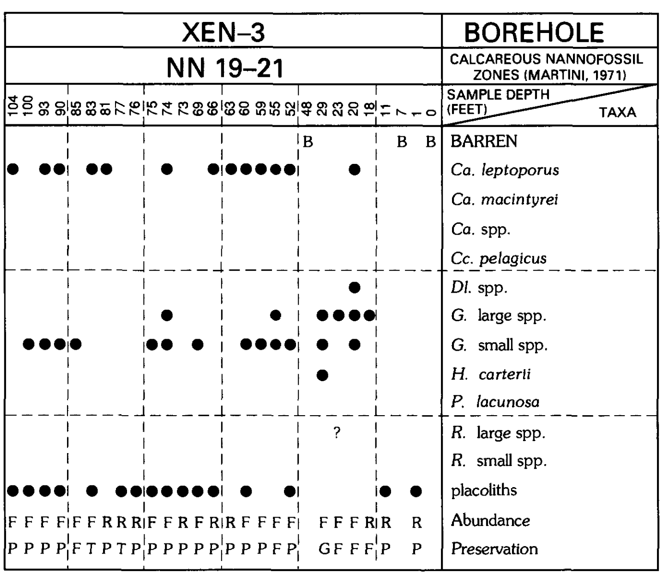


FIGURE 7.—Calcareous nannofossil occurrences in boreholes KAR–1 and XEN–3. See figure 3 for an explanation of abundance, preservation, and other symbols used on the figure.

Zone AA	*Neonesidea schulzi* Zone
Zone BB/CC	*Cletocythereis marshallensis Zone, Bairdoppilata* Subzone
Zone DD	*Cletocythereis marshallensis, Paracytheridea tschoppi* Subzone
Zone EE/FF	*Loxoconcha-Xesotoleberis* Zone
Zone GG	*Radimella-Hermanites* Zone
Zone HH	*Bosasella* Zone
Zone II	*"Procythereis" teeteri* Zone
Zone JJ	Miocyprideis Zone
Zone KK	*Stigmatocythere spinosa* Zone
Upper Zone LL	*"Capricornia," Neomonoceratina* Zone
Middle Zone LL	*Pokornyella pseudojaponica* Zone
Lower Zone LL	*Tenedocythere setigera* Zone
Zone MM	*?Pokornyella* sp. b Zone

Calcareous nannofossil and planktic foraminiferal zonal assignments are plotted on separate columns for each borehole (fig. 8). For ease in comparison and interpretation, planktic foraminiferal zonal assignments also are converted to calcareous nannofossil zonal equivalents by using the calibrations of Berggren and others (1985). By using the local benthic zones as a biostratigraphic framework, we were able to compare the scattered calcareous nannofossil and planktic foraminiferal age data from borehole to borehole and to calibrate the local benthic zonation to internationally recognized planktic zonations for the PEACE boreholes (fig. 8).

ZONE MM

Zone MM was used by Cronin and others (1986) to include all the strata from the bottom of the PEACE boreholes to the base of Zone LL. No planktic foraminiferal calibrations are available for Zone MM. The only diagnostic calcareous nannofossil found in Zone MM is *Discoaster variabilis*, which occurs at 876 ft in KBZ–4. This species indicates an age no older than Zone NN 5 or middle Miocene. The boundary between Zones MM and LL in this core is equivocal, and the occurrence of *D. variabilis* in KBZ–4 may actually fall within lower Zone LL.

LOWER ZONE LL
(NANNOFOSSIL ZONES NN 5–7, MIDDLE MIOCENE)

Zone LL was subdivided into lower Zone LL, middle Zone LL, and upper Zone LL, on the basis of ostracodes. Middle Zone LL cannot be dated on the basis of calcareous nannofossils or planktic foraminifers and is not discussed in this paper. In borehole OOR–17, lower Zone LL is constrained to the interval of Zones N 9–13 (NN 5–7), on the basis of the occurrence of the planktic foraminifers *Orbulina universa* and *Globigerinoides subquadratus* at 930 ft. Borehole OBZ–4 also has these same two species in the lower Zone LL at 808 ft. In KBZ–4, lower Zone LL is constrained to the middle Miocene by the occurrence of *G. subquadratus* at 864 ft (ranges no higher than Zone N 13 or NN 5–7) and the occurrence of *Discoaster variabilis* at 876 ft (ranges no lower than NN 5). Therefore, lower Zone LL occurs within calcareous nannofossil Zones NN 5–7.

UPPER ZONE LL
(NANNOFOSSIL ZONE NN 9—LATE MIOCENE)

In KAR–1, the co-occurrence of *Discoaster pentaradiatus* and *D. calcaris* at 852 ft dates upper Zone LL as Zones NN 9–10. Furthermore, the presence of *Discoaster hamatus* (confined to Zone NN 9) in the overlying Zone KK further restricts the assignment of upper LL to Zone NN 9. This assignment is supported by planktic foraminifers from upper Zone LL in OAR–2 and 2A.

LOWER ZONE KK
(NANNOFOSSIL ZONE NN 9—LATE MIOCENE)

In OOR–17, lower Zone KK falls within Zones NN 9 and 10, on the basis of the occurrences of *Discoaster pentaradiatus* (FAD in Zone NN 9) at 813 ft and *Discoaster prepentaradiatus* (LAD in Zone NN 10) at 777 ft. In KBZ–4, the sample at 777 ft is definitely in Zone NN 9, on the basis of the occurrence of *Discoaster hamatus* (FAD and LAD in Zone NN 9). The lower part of KK is confined to Zones NN 9–11 in KAR–1, on the basis of the occurrences of *Discoaster pentaradiatus* (FAD in Zone NN 9) at 852 ft and *Discoaster quinqueramus* (LAD in Zone NN 11) at 741 ft. By combining these data, the lower part of Zone KK is within Zone NN 9.

UPPER ZONE KK AND ZONE JJ
(NANNOFOSSIL ZONE NN 11—LATE MIOCENE)

Upper Zone KK and Zone JJ are constrained to Zone NN 11 in KBZ–4 by the presence of *Discoaster quinqueramus* (FAD and LAD in Zone NN 11) between 756 ft and 575 ft. In KAR–1, *D. quinqueramus* occurs at 741 ft in Zone KK, and *Discoaster berggrenii* occurs at 626 ft (Zone JJ); these occurrences confine this interval to Zone NN 11. Moreover, Zone JJ is assigned to Zone NN 11 in OAR–2 and 2A on the basis of the presence of *D. berggrenii* at 659 ft. Therefore, upper Zone KK and Zone JJ are assigned to Zone NN 11 or the late Miocene.

ZONES II, HH, AND GG (NANNOFOSSIL ZONES NN 12–15—EARLY PLIOCENE)

The middle part of Zone II in KAR–1 contains the planktic foraminifers *Globorotalia ungulata* and *Globigerina nepenthes* at 557 ft; these species occur together only in Pliocene Zone N 19 (Zones NN 12–15). Because such a thick sequence of Zone NN 11 occurs within KK and JJ, and because *D. quinqueramus* and *D. berggrenii* do not occur in Zone II, Zone II probably is confined to Zone NN 12 or younger (Pliocene). Thus, all of Zone II most likely is Pliocene in age, and the Miocene-Pliocene boundary in the PEACE boreholes is placed at the JJ–II boundary.

Sediments from Zone HH are highly recrystallized, and planktic microfossils are very sparse. However, an assemblage from Zone HH in KBZ–4 is referable to Zone N 19 (Zones NN 12–15). Assemblages in Zone GG from OAR–2 and 2A indicate that Zone GG is still within Pliocene Zones N 19–21 (Zones NN 12–16), on the basis of both planktic foraminifers and calcareous nannofossils. Note that we assume that the highest LAD's of *Reticulofenestra pseudoumbilica* and *Sphenolithus* found in Enewetak cores are probably the closest to their actual extinction levels. Therefore, we judge that the top of Zone NN 15 occurs near the top of Zone GG and that Zones II, HH, and GG correlate with Zones NN 12–15.

ZONE EE/FF (PREDOMINANTLY LOWER NANNOFOSSIL ZONE NN 19—LATE PLIOCENE)

The occurrence of a few specimens of *Sphaeroidinellopsis* spp. in samples from the lowest interval assigned to Zone EE/FF in KBZ–4, OOR–17, and XEN–3 suggests that the lower part of EE/FF may be within the Pliocene Zone N 19 (Zones NN 12–16). This interpretation is supported by the presence of *Pseudoemiliania lacunosa* (FAD in uppermost Zone NN 15) and the absence of *Sphenolithus* species (LAD at the top of Zone NN 15) at 292 ft (base of Zone EE/FF) in OOR–17. However, most occurrences of planktic microfossils above the base of Zone EE/FF indicate assignment to Zone NN 19. In borehole OOR–17, *Gephyrocapsa* small species first occurs at 194 ft, and *Gephyrocapsa* large species first occurs at 137 ft; both of these horizons are within the upper part of Zone EE/FF. Both *Gephyrocapsa* large species and *Gephyrocapsa* small species first occur at 248 ft in XEN–3; this occurrence is 42 ft above the base of Zone EE/FF. In KBZ–4, *Gephyrocapsa* small species and *Gephyrocapsa* large species both first occur at 206 ft; this occurrence is 29 ft above the base of Zone EE/FF. Assuming that the first appearance of *Gephyrocapsa* large species occurs near the base of Zone NN 19, then all of Zone EE/FF above the first *Gephyrocapsa* large species can be no older than Zone NN 19. *Calcidiscus macintyrei* (LAD in the lower part of Zone NN 19) does not occur above 187 ft in KBZ–4; this occurrence is in the middle part of Zone EE/FF. *Calcidiscus macintyrei* has a last definite occurrence at 183 ft in KAR–1, and this depth is near the middle of Zone EE/FF. The presence of *Calcidiscus macintyrei* in EE/FF further restricts the age to lower Zone NN 19. The absence of *C. macintyrei* in the uppermost part of Zone EE/FF indicates that this portion of EE/FF is above the extinction of *C. macintyrei* and thus within the Pleistocene, according to Berggren and others (1985).

ZONE DD (UPPER NANNOFOSSIL ZONE NN 19—PLEISTOCENE)

Zone DD cannot be dated directly by planktic microfossils, except for one occurrence of *Pseudoemiliania lacunosa* (LAD at top of Zone NN 19) in KAR–1 at 118 ft (1 ft below the top of Zone DD). Available radiometric determinations suggest that Zone DD is referable to uppermost Zone NN 19 or NN 20 (see Radiometric Dating section).

ZONES CC, BB, AND AA (NANNOFOSSIL ZONES NN 19–21—PLEISTOCENE)

The occurrence of *Pseudoemiliania lacunosa* in KAR–1 at 100 and 95 ft places the lower portion of Zone CC within Zone NN 19. The remainder of Zones CC, BB, and AA cannot be subdivided by using calcareous nannofossils or planktic foraminifers. They are no older than Zone NN 19, on the basis of the presence of the genus *Gephyrocapsa*, although these zones are probably confined to Zones NN 20 and 21, on the basis of radiometric dating (see following section). However, this assignment cannot be made on the basis of calcareous nannofossils. The paucity of *Pseudoemiliania lacunosa* specimens (LAD at top of Zone NN 19) throughout the PEACE boreholes indicates that the absence of *P. lacunosa* in this interval is not a significant biostratigraphic indicator.

RADIOMETRIC DATING

Previous shallow drilling carried out during the Pacific Atoll Cratering Experiment (PACE) (Henny and others, 1974) and EXPOE (Couch and others, 1975) recovered a suite of samples and cores from a number of islands in the northern part of the Enewetak Atoll. Study of this material, including XEN–3, allowed recognition and correlation of six stratigraphic intervals within the upper 230 ft of the atoll sequence that can be correlated within

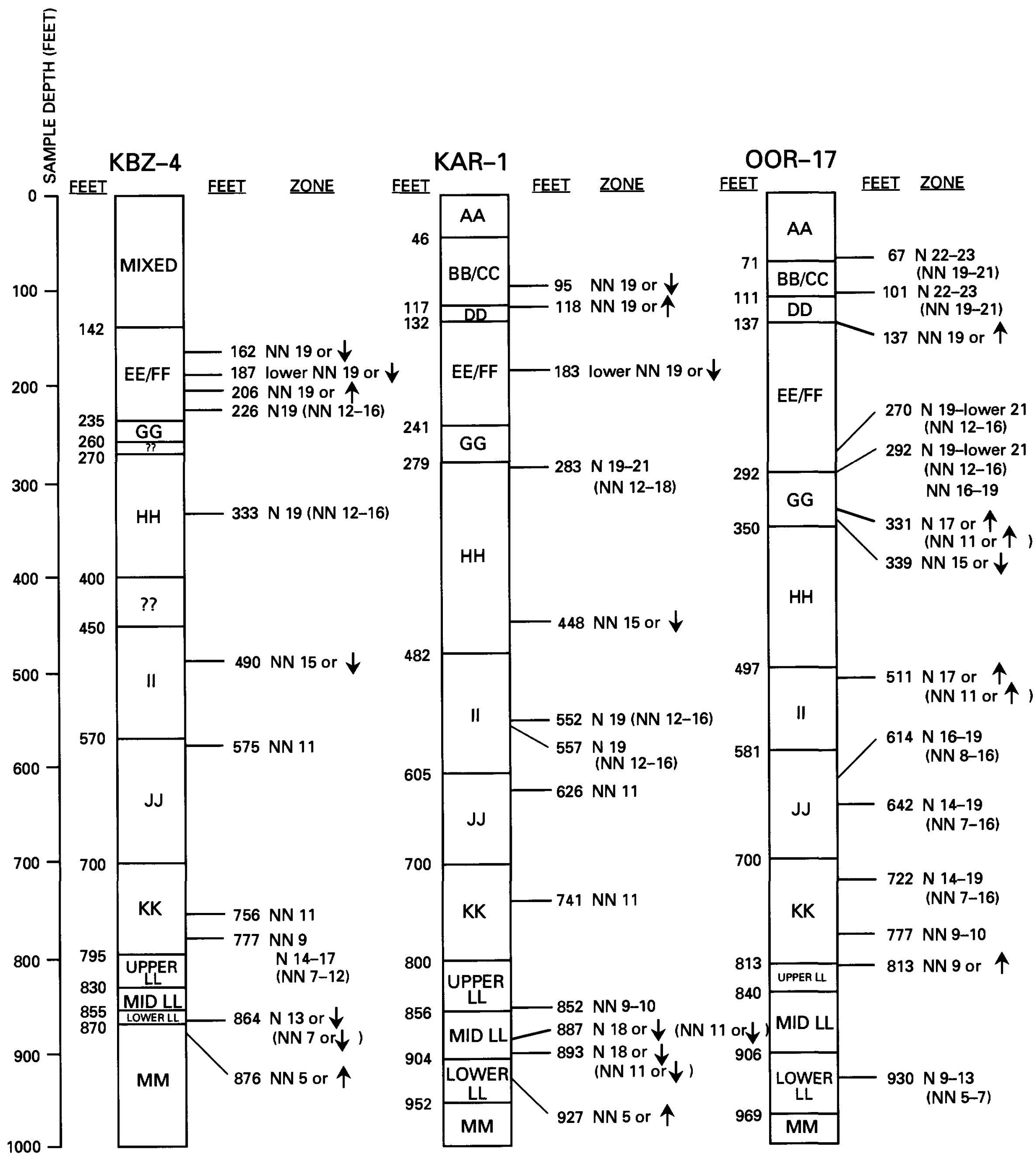


FIGURE 8.—Combined calcareous nannofossil and planktic foraminiferal age dates for boreholes KBZ–4, KAR–1, OOR–17, OAR–2 and 2A, and XEN–3 and final age assignment for each Enewetak benthic zone. Calcareous nannofossil and planktic foraminiferal zone assignments for diagnostic samples in each core are shown. Footages are subbottom. In the case of planktic foraminiferal zones, equivalent calcareous nannofossil zones as determined by the correlation chart of Berggren and others (1985) are given in parentheses. Zonation assignments for Enewetak benthic zones have been integrated into a composite, showing the overall relationship of calcareous nannofossil zones to the Enewetak benthic zonation and resulting age assignments. An up arrow indicates that the zonal assignment may be younger. A down arrow indicates that the zonal assignment may be older.

and between islands (Couch and others, 1975). Radiocarbon and uranium-series dates are available from two cores, PAR–15 and PAR–16, from Aranit Island (Szabo and others, 1985). The uppermost interval or interval 1 was dated at 8,000 yr by radiocarbon. Uranium series dating of intervals 2 and 4 yielded ages of 131,000 ± 3,000 yr and 454,000 ± 100,000 yr, respectively. No dates were obtained from intervals 3, 5, or 6.

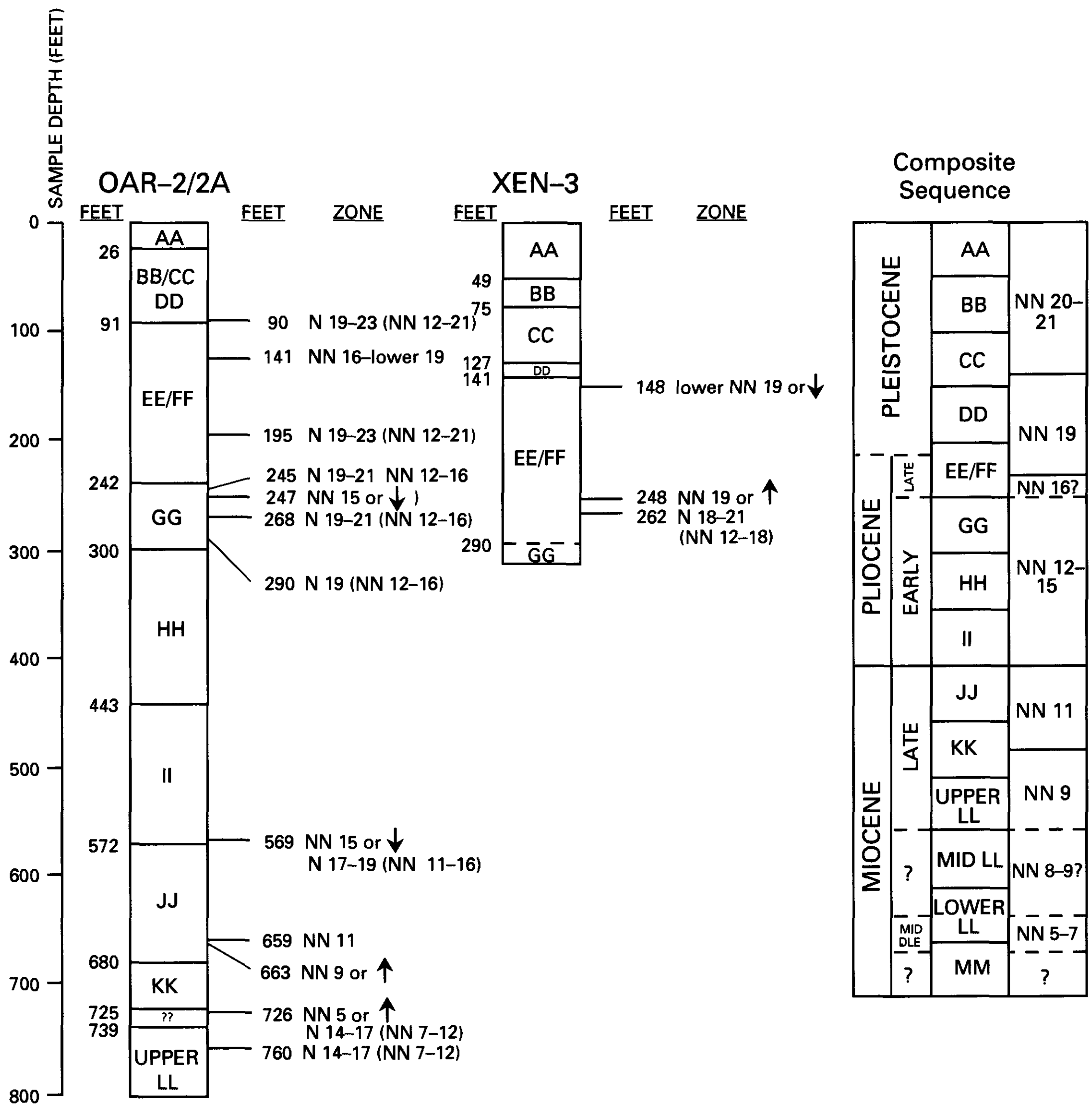


FIGURE 8.—Continued

Although we have not examined samples from PAR–15 and PAR–16 for calcareous nannofossils or planktic foraminifers, the relation between the dated stratigraphic intervals in these boreholes and the benthic zonation identified in XEN–3 from Engebi Island is reasonably clear. Interval 1 of Szabo and others (1985) represents sediments deposited during the Holocene and can be identified readily by the presence of bright red specimens of the encrusting foraminifer *Homotrema* and a pronounced solution surface at its base in core samples from the islands and the lagoon. Interval 1 contains Zone AA benthic microfossils in XEN–3 and all other boreholes that were examined during project PEACE.

Following the stratigraphic correlation of Couch and others (1975), interval 2 of Szabo and others (1985) correlates with Zone BB and perhaps part of Zone CC in XEN–3, and interval 4 correlates with Zone CC and possible Zone DD. Thus, radiocarbon and uranium-series dates of 454,000 yr or less for Zones AA–DD corroborate a Pleistocene assignment for these sediments.

CONCLUSIONS

As a result of this study on Enewetak PEACE borehole samples, a composite biostratigraphic sequence was established (fig. 8) that integrates all calcareous nannofossil and planktic foraminiferal data into the benthic zonation of Cronin and others (1986) and Cronin (written commun., 1990). Although individual cores contain a limited number of reliable, planktic calibration points, the composite data for Enewetak benthic Zones LL–AA can be correlated with the international planktic zonations and the time scale of Berggren and others (1985).

Our correlations indicate that lower Zone LL is middle Miocene in age and upper Zones LL–JJ are late Miocene. Upper Zone LL and the lower part of Zone KK correlate with calcareous nannofossil Zone NN 9, and the upper part of Zone KK and Zone JJ correlate with calcareous nannofossil Zone NN 11. The position of the middle-late Miocene boundary is poorly controlled but occurs within lower to middle Zone LL. The Miocene-Pliocene boundary is at or near the boundary between Zones JJ and II. Zones II–GG are early Pliocene (calcareous nannofossil Zones NN 12–15). Part of Zone EE/FF may be referable to late Pliocene Zone NN 16, but most of Zone EE/FF correlates with nannofossil Zone NN 19. The Pliocene-Pleistocene boundary is within Zone EE/FF. Zones DD–AA are assigned to the Pleistocene on the basis of both paleontologic and radiometric data. Zones DD and CC most likely represent sediments deposited during two separate late Pleistocene interglacials (marine isotope stages 9, 11, or 13; Szabo and others, 1985). Zone BB represents sediments deposited during the last interglacial period, whereas Zone AA represents the Holocene.

The late Cenozoic sedimentary record at Enewetak reflects the complex interaction of a fluctuating sea level and a subsiding atoll. Although our stratigraphic resolution is not sufficient to discern individual, high-frequency, sea-level events older than the latest Pleistocene, we can identify intervals where the record suggests changes in the frequency and amplitude of sea-level fluctuations. The relatively thin and discontinuous late Pliocene and Pleistocene section preserved at Enewetak represents an interval of generally lower and unstable sea level associated with late Neogene glacial-interglacial cycles. The relatively thick early-to-middle Pliocene section, which has few obvious disconformities, indicates an interval of high and relatively stable sea level for parts of this interval. Late Miocene Zone NN 11 also is well represented in the Enewetak section; its presence suggests that part of the late Miocene was also an interval of relatively high and stable sea level.

LIST OF SPECIES FOUND IN BOREHOLES AT ENEWETAK

CALCAREOUS NANNOFOSSILS

Braarudosphaera bigelowii (Gran & Braarud, 1935) Deflandre, 1947
Calcidiscus leptoporus (Murray & Blackman, 1898) Loeblich & Tappan, 1978
Calcidiscus macintyrei (Bukry & Bramlette, 1969) Loeblich & Tappan, 1978
Ceratolithus acutus Gartner & Bukry, 1974
Coccolithus eopelagicus (Bramlette & Riedel, 1954) Bramlette & Sullivan, 1961
Coccolithus pelagicus (Wallich, 1877) Schiller, 1930
Dictyococcites bisectus (Hay, Mohler, & Wade, 1966) Bukry & Percival, 1971
Discoaster aulakos Gartner, 1967
Discoaster berggrenii Bukry, 1971
Discoaster bollii Martini & Bramlette, 1963
Discoaster brouweri Tan, 1927 emend. Bramlette & Riedel, 1954
Discoaster calcaris Gartner, 1967
Discoaster challengeri Bramlette & Riedel, 1954
Discoaster deflandrei Bramlette & Riedel, 1954
Discoaster exilis Martini & Bramlette, 1963
Discoaster hamatus Martini & Bramlette, 1963
Discoaster moorei Bukry, 1971
Discoaster neohamatus Bukry & Bramlette 1969
Discoaster nephados Hay in Hay and others (1967)
Discoaster pansus (Bukry & Percival, 1971) Bukry, 1973
Discoaster pentaradiatus Tan, 1927 emend. Bramlette & Riedel, 1954
Discoaster prepentaradiatus Bukry & Percival, 1971
Discoaster quinqueramus Gartner, 1969
Discoaster signus Bukry, 1971
Discoaster subsurculus Gartner, 1967
Discoaster surculus Martini & Bramlette, 1963
Discoaster variabilis Martini & Bramlette, 1963
Discoaster woodringi Bramlette & Riedel, 1954
Helicosphaera carteri (Wallich, 1877) Kamptner, 1954
Helicosphaera lophota (Bramlette & Sullivan, 1961) Locker, 1973
Helicosphaera recta (Haq, 1966) Jafar & Martini, 1975
Pseudoemiliania lacunosa (Kamptner, 1963) Gartner, 1969
Reticulofenestra pseudoumbilica (Gartner, 1967) Gartner, 1969
Reticulofenestra umbilica (Levin, 1965) Martini & Ritzkowski, 1968
Rhabdosphaera procera Martini, 1969
Schphosphaera apsteinii Lohmann, 1902
Schphosphaera intermedia Deflandre, 1942
Schphosphaera pulcherrima Deflandre, 1942
Sphenolithus abies Deflandre in Deflandre & Fert (1954)
Zygrhablithus bijugatus (Deflandre in Deflandre & Fert (1954)) Deflandre, 1959

PLANKTIC FORAMINIFERS

Globigerina angulisuturalis Bolli
Globigerina bulloides d'Orbigny
Globigerina ciperoensis Bolli
Globigerina decoraperta Takayanagi and Saito
Globigerina nepenthes Todd

Globigerina rubescens Hofker
Globigerina woodi Jenkins
Globigerinella aequilateralis (Brady)
Globigerinita glutinata (Egger)
Globigerinoides conglobatus (Brady)
Globigerinoides extremus Bolli and Bermudez
Globigerinoides obliquus Bolli (s.l.)
Globigerinoides ruber (d'Orbigny)
Globigerinoides sacculifer (Brady)
Globigerinoides subquadratus Bronnimann
Globigerinoides tenellus Parker
Globoquadrina altispira (Cushman and Jarvis)
Globoquadrina dehiscens (Chapman, Parr, and Collins)
Globorotalia kugleri Bolli
Globorotalia menardii (Parker, Jones, and Brady)
Globorotalia miocenica Palmer
Globorotalia plesiotumida Blow and Banner
Globorotalia tumida (Brady)
Globorotalia ungulata Bermudez
Neogloboquadrina acostaensis (Blow)
Neogloboquadrina humerosa (Takayanagi and Saito)
Orbulina universa d'Orbigny
Pulleniatina obliquiloculata (Parker and Jones)
Pulleniatina primalis Banner and Blow
Sphaeroidinellopsis spp.
Streptochilus spp.

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19. Assemblages found between 777 ft and 333 ft can be assigned only to the broad interval from Zone N 14 to Zone N 19 or late middle Miocene to Pliocene.