



Larger Foraminifer Biostratigraphy of PEACE Boreholes, 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-D

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By THOMAS G. GIBSON *and* RICHARD MARGERUM

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*Larger foraminiferal and some smaller foraminiferal data from
Enewetak Atoll boreholes were integrated into a local benthic
foraminiferal and ostracode biostratigraphy for correlation with Pacific
biostratigraphic sequences*



DEPARTMENT OF THE INTERIOR

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U.S. GEOLOGICAL SURVEY

Dallas L. Peck, *Director*

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Library of Congress Cataloging in Publication Data

Gibson, Thomas G.

Larger foraminifer biostratigraphy of PEACE boreholes, Enewetak Atoll, western Pacific Ocean / by Thomas G. Gibson and Richard Margerum.

p. cm.—(Geologic and geophysical investigations of Enewetak Atoll, Republic of the Marshall Islands : D) (U.S. Geological Survey professional paper ; 1513-D)

Includes bibliographical references.

Supt. of Docs. no. : I 19.16: 1513-D

1. Foraminifera, Fossil. 2. Paleontology—Miocene. 3. Paleontology—Pleistocene. 4. Paleontology—Marshall Islands—Enewetak Atoll. 5. Pacific Enewetak Atoll Crater Exploration Program. I. Margerum, Richard. II. Title. III. Series. IV. Series: Geologic and geophysical investigations of Enewetak Atoll. Republic of the Marshall Islands ; ch. D.

QE772.G43 1992

563'N.12—dc20

91-10889

CIP

For sale by the Books and Open-File Reports Section, U.S. Geological Survey,
Federal Center, Box 25425, Denver, CO 80225

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GEOLOGIC AND GEOPHYSICAL INVESTIGATIONS OF ENEWETAK ATOLL, REPUBLIC OF THE MARSHALL ISLANDS

LARGER FORAMINIFER BIOSTRATIGRAPHY OF PEACE BOREHOLES, ENEWETAK ATOLL, WESTERN PACIFIC OCEAN

By THOMAS G. GIBSON and RICHARD MARGERUM

ABSTRACT

Larger foraminiferal assemblages, including *Lepidocyclina orientalis*, *Miogypsina thecidaeiformis*, *Miogypsinoidea dehaartii*, *Spiroclypeus margaritatus*, *Miogypsinoidea ubaghsi*, *Heterostegina bornensis*, and *Lepidocyclina ephippoides*, and a smaller foraminifer, *Austrotrillina striata*, are used to correlate upper Oligocene and lower Miocene strata in the Pacific Atoll Exploration Program (PEACE) boreholes at Enewetak Atoll, Republic of the Marshall Islands, western Pacific Ocean, with the Te and Tf zones of the previously established Tertiary Far East Letter Zonation. Correlation using these two benthic groups is critical because calcareous nannofossils and planktic foraminifers are absent in the lower Miocene strata. The deepest PEACE borehole, OBZ-4, has abundant diagnostic larger foraminifers throughout the upper Oligocene to middle Miocene strata. The three larger foraminiferal species found in the upper Miocene strata continue into the present-day assemblages. Three new subdivisions are proposed within the oldest local biostratigraphic Zone MM previously established for the Enewetak PEACE cores.

Biostratigraphic data from these boreholes delineate a thick (greater than 700 feet) sequence of upper Oligocene and lower Miocene strata corresponding to lower and upper Te zone. These strata document a major period of carbonate accumulation at Enewetak during the Late Oligocene and early Miocene (26 to 18 million years ago).

INTRODUCTION

PURPOSE AND SCOPE

The Pacific Enewetak Atoll Crater Exploration (PEACE) Program drilled 32 shallow- to moderate-depth boreholes in the northern and northwestern part of Enewetak Lagoon, Republic of the Marshall Islands, during 1985 from the drill ship M/V *Knut Constructor* (fig. 1). The PEACE boreholes were drilled and sampled with a combination of split spoon, hammer, and coring methods and had a generally good recovery of about 50

percent in the intermixed hard and soft sediments (Henry and others, 1986). The deepest PEACE borehole, OBZ-4, penetrated to approximately 1,800 ft below sea level (bsl).

Earlier deep holes drilled at Bikini in the late 1940's and at Enewetak in the early 1950's (Emery and others, 1954; Ladd and Schlanger, 1960) had only a few thin cored intervals, and the foraminiferal faunas were studied mostly from cuttings. These earlier drill hole samples indicated that about 4,200–4,600 ft of Eocene and younger carbonate strata overlie the volcanic basement rocks in Enewetak Atoll (Todd and Low, 1960).

The smaller benthic foraminiferal and ostracode assemblages from five PEACE boreholes and from three boreholes (XEN-3, XSA-1, and XRI-1, fig. 1) of the earlier Exploratory Program on Enewetak (Project EXPOE), drilled and sampled by a combination of split spoon and coring in 1973–74 (Couch and others, 1975), were used to construct a local biostratigraphic zonation for the middle Miocene to Holocene strata of the Enewetak holes (Cronin and others, 1986). However, smaller benthic species are difficult to use for long-distance biostratigraphic correlation over the Pacific. Most tropical areas of the Pacific have no long cores available, and outcrop sections provide only a fragmentary record. Thus, documenting first and last appearance datums of most benthic species is difficult.

The correlation of Enewetak deposits using intercontinental planktic zonations is difficult because the deposits commonly represent shallow, reef environments that yield sparse planktic components. For example, the study of calcareous nannofossils and planktic foraminifers from the PEACE and EXPOE boreholes contributes some tie points in the middle Miocene and younger strata with the intercontinental zonations (Bybell and Poore, this volume), but calcareous plankton generally are sparse. Further, calcareous plankton become sparse

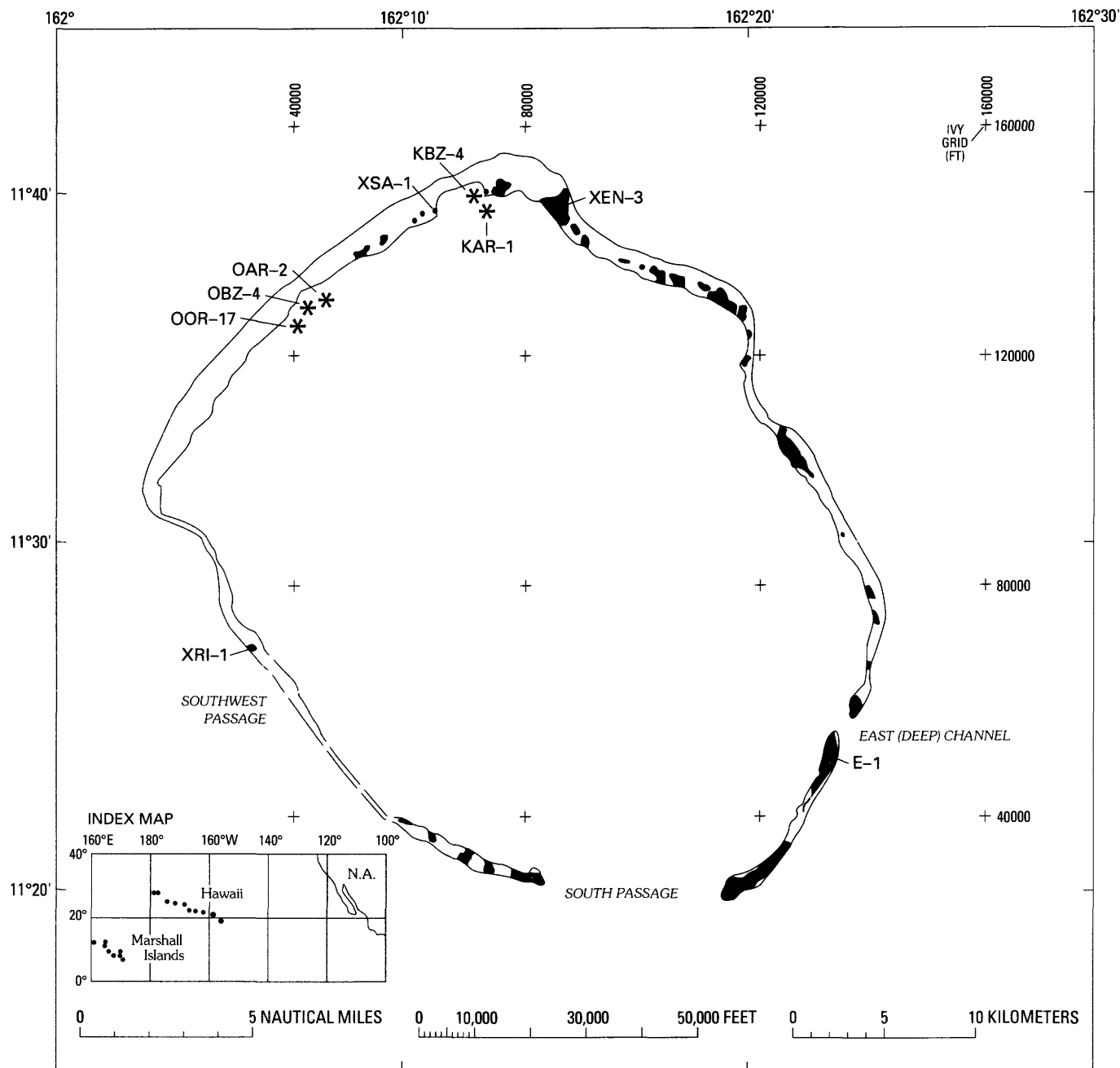


FIGURE 1.—Location of the five deepest PEACE boreholes, three EXPOE boreholes, and drill hole E-1 at Enewetak Atoll.

and poorly preserved, presumably because of diagenetic effects, in the interval from 900 to 1,150 ft bsl in the PEACE boreholes; they are absent in all samples below 1,150 ft bsl.

In these intervals where calcareous plankton are absent, both large and small benthic species must be used. Larger foraminiferal age assignments are particularly important in the upper Oligocene and lower Miocene strata, which occur deeper than 900 ft bsl in the PEACE boreholes. Well-preserved larger foraminifers

are present in most intervals in these older strata. Some smaller benthic species are present in the lower Miocene strata, and one of these, *Austrotrillina striata*, commonly has been incorporated into western Pacific biostratigraphic zonations (Adams, 1984; Chaproniere, 1984).

This paper documents the occurrences of larger foraminiferal assemblages and a few critical smaller benthic species in the upper Oligocene to Holocene strata in five of the PEACE and three of the EXPOE boreholes. We

BOREHOLE	THICKNESS OF STRATA PENETRATED (FEET)	DEPTH BELOW SEA LEVEL OF BOREHOLE SITE (FEET)
KAR - 1	1,146	105
KBZ - 4	1,046	109
OAR - 2	886	114
OBZ - 4	1,605	199
OOR - 17	1,091	55

FIGURE 2.—Thickness of strata penetrated and depth below sea level of the deepest PEACE borehole sites at Enewetak Atoll (data from Henry and others, 1986).

then correlate these occurrences in Enewetak with the known biostratigraphic distribution of larger foraminifers in the western Pacific to give some age assignment to the older portions of the PEACE boreholes.

ACKNOWLEDGMENTS

The large number of samples examined during this study involved a considerable amount of preparation by Elizabeth E. Hill and Craig Montgomery, and their help is greatly appreciated.

The authors are indebted to C.G. Adams for his advice on the identification of *Austrorillina* species and the age significance of some larger foraminifers. Warren Blow of the Department of Paleobiology of the Natural History Museum of the Smithsonian Institution kindly facilitated the location and sampling of the E-1 core from Enewetak. Laurel Bybell, George Chaproniere, Thomas Cronin, and Richard Poore made many helpful suggestions on the manuscript.

MATERIALS AND METHODS

More than 1,000 samples from all 32 PEACE boreholes and from 3 of the EXPOE boreholes were examined for benthic foraminifers. Diagnostic larger foraminifers were obtained only from the five deepest PEACE boreholes, KAR-1, KBZ-4, OAR-3, OBZ-4, and OOR-17 (fig. 1). The thickness of the penetrated section and elevations of the PEACE boreholes in relation to the sea floor and sea level are given in figure 2.

All samples examined were composed of carbonate sediments of various degrees of induration. The samples were processed in U.S. Geological Survey laboratories in Reston, Va. They were soaked in water containing sodium carbonate and a calgon solution and agitated for several hours on a shaker; the more indurated samples then were treated with a 10-percent hydrogen peroxide solution to aid in their breakdown.

After soaking, the samples were washed through a set of sieves having screen sizes between 840 and 63 microns. Smaller benthonics generally were examined from a number of sieve sizes ranging from 840 to 150 microns. Larger foraminifers were collected largely from the 840- and 420-micron sieves.

Thin sections were used to identify the larger foraminifers; three to four horizontal and one to two vertical sections normally were made of each species per sample.

PREVIOUS FORAMINIFERAL STUDIES

Previous work on larger foraminiferal biostratigraphy in the western Marshall Islands was on drill hole samples from Bikini (Cole, 1954) and Enewetak (Cole, 1957). Companion studies of smaller foraminiferal biostratigraphy from the same drill holes were made by Todd and Post (1954) from Bikini and Todd and Low (1960) from Enewetak. These studies were based largely upon drill hole cuttings. Because these authors recognized considerable downhole contamination of foraminiferal specimens in the cuttings, their studies concentrated almost exclusively on the last appearance datums (LAD) of species; they did not attempt to give the first appearance datums (FAD) from the drill hole cuttings. Thus comparing the overall depth and age range of species between the previous studies and the present one is not possible. The coring, split spoon, and hammer sampling procedures used in the PEACE project drilling resulted in relatively precise depth information, particularly on the FAD of foraminiferal species and, thus, their total stratigraphic ranges.

The considerable similarity in the highest occurrence depths of many foraminiferal species between the older studies and the PEACE Project borehole samples is a tribute to the effort and diligence of both the foraminiferal workers and the drilling crew of the original drill holes.

We relate the larger foraminiferal stratigraphic ranges in the PEACE boreholes first to the Tertiary Far East Letter Classification of Van der Vlerk and Umbgrove (1927) and then to the planktic foraminiferal global zonation and the Cenozoic series and stages following the studies of Adams (1984) and Chaproniere (1984). Van der Vlerk and Umbgrove (1927) developed the Tertiary Far East Letter Classification (hereafter, informally referred to as the Tertiary Far East Letter Zonation (TFELZ)) in the Netherlands East Indies. Initially, the TFELZ was used for regional biostratigraphic work in the Indo-West Pacific, and there was little or no attempt at detailed correlation of these letter zones with the European Tertiary Stages. During the past 15 years, however, studies conducted on planktic foraminifers and

calcareous nannofossils in the Pacific and Indian Oceans have resulted in generalized correlation of the TFELZ with intercontinental microfossil zones and European Stages (Haak and Postuma, 1975; Adams, 1984; and Chaproniere, 1984) (fig. 3).

The papers cited indicate that enough is presently known of larger foraminiferal biostratigraphy that it can be used to document the general age assignment of the older strata in the Enewetak PEACE boreholes, although more biostratigraphic tie points between the larger foraminiferal species first and last appearance datums in the Pacific and the intercontinental calcareous plankton zones are desirable to more precisely document the Oligocene and Miocene correlations.

Cole's two Marshall Island larger foraminiferal studies (1954; 1957) were published prior to the advent of the numerous Pacific planktic microfossil studies and, thus, before the general correlation of the TFELZ into the global planktic zonations and the European Stages. As a result of new correlations of the TFELZ, some changes are made here from the prior stage or series assignments made by Cole (1957) for the strata containing larger foraminiferal faunas in Enewetak. One particularly important change in age designation in the TFELZ is the correlation by Adams (1984) and Chaproniere (1984) of the upper part of Te (=Te 5) with an early Miocene age and the lower part of Te (=Te 1-4) with a late Oligocene age (fig. 3). Cole's older studies placed all of Te in the lower Miocene.

Enewetak strata containing diagnostic larger foraminifers are confined to the Te and Tf divisions of the TFELZ. Although the Te-Tf boundary was placed in planktic foraminiferal Zones N 7-8 by Haak and Postuma (1975), Adams (1984) and Chaproniere (1984) now place this boundary within Zone N 6 (fig. 3). The upper Te (=Te 5) -lower Te (=Te 1-4) boundary in the above three studies, as well as in Hashimoto and others (1977), corresponds with the Oligocene-Miocene boundary.

LARGER FORAMINIFERAL OCCURRENCES, ZONATION, AND AGE ASSIGNMENTS

Larger foraminifers occur in most sample intervals in all Enewetak PEACE boreholes. The 27 shallow-depth PEACE boreholes, however, penetrated only into the uppermost 100 to 300 ft of the sedimentary column; these shallower depths are composed of Pliocene and Pleistocene strata and contain only a few long-ranging larger foraminiferal species.

The five deepest PEACE boreholes, KAR-1, KBZ-4, OAR-2, OBZ-4, and OOR-17, penetrated to depths greater than 500 ft. Additional genera and species of larger foraminifers appear in the middle Miocene and older strata found in the middle to lower parts of these boreholes. These include species of *Heterostegina*, *Lepi-*

Series	European Stages		Planktic Foraminiferal Zones (Blow, 1969)	Tertiary Far East Letter Zones
PLEISTOCENE	U.	CALABRIAN	N23	Tg/h
		PIACENZIAN	N19	
		ZANCLIAN	N18	
MIOCENE	UPPER	MESSINIAN	N17	Tf ₃
		TORTONIAN	N16	
			N15	
	MIDDLE	SERRA - VALLIAN	N14	Tf ₂
			N11	
			N10	
			N9	
	LOWER	LANGHIAN	N8	Tf ₁
			N7	
		BURDI - GALIAN	N6	
			N5	
			N4	
OLIGOCENE	UPPER	CHATTIAN	P22	Te ₁₋₄ (lower Te)
			N3	
			P21	
			N2	
	LOWER	RUPELIAN	P20	Td
			N1	
			P19	
			P18	Tc

FIGURE 3.—Correlation of Tertiary Far East Letter Zones, planktic foraminiferal zones, and European Stages (from Adams, 1984, with some addition to and modification of nomenclature).

docyclina, *Miogypsina*, *Miogypsinoides*, and *Spiroclipeus*, some of which have widespread biostratigraphic utility and are diagnostic of late Oligocene and early Miocene times. The larger foraminiferal assemblages at Enewetak contain some diagnostic biostratigraphic species of the Indo-Western Pacific area. However, the number of larger foraminiferal species at Enewetak is fairly low in comparison to some coeval assemblages found farther west in larger Indo-Western Pacific land masses.

Four boreholes contain only the upper part of the diagnostic larger foraminiferal sequence because of the shallower terminal depth of the holes. Diagnostic species are found in shorter intervals of about 200 ft in KAR-1 and KBZ-4, about 140 ft in OOR-17, and just a few feet in OAR-2. However, diagnostic species occur through a 728-ft interval in OBZ-4, the deepest PEACE borehole, and this hole provides the best developed sequence of larger foraminiferal assemblages and yields the oldest fossiliferous material sampled in the PEACE boreholes.

The diagnostic larger foraminiferal species that occur in the PEACE boreholes are discussed from the highest of the local Enewetak zones (AA) established by Cronin and others (1986) to the oldest (MM). The occurrences and abundances of larger foraminifera in the five deepest PEACE boreholes are given in figures 4-7. The stratigraphic ranges of the larger foraminifer species in the five deepest PEACE boreholes, as well as some smaller benthic species discussed below, in relation to the local Enewetak benthic zones are given in figure 8. The taxonomic concepts used in the present paper follow those of Cole (1957, 1975) unless otherwise mentioned. The correlation of the middle Miocene to Holocene Enewetak benthic zones with intercontinental planktic zonations is from the work of Bybell and Poore (this volume).

Zones AA-HH. These upper zones established in the PEACE boreholes are of middle Pliocene to Holocene age on the basis of the planktic foraminifera and calcareous nannofossils. They contain only three larger foraminiferal species, *Heterostegina suborbicularis* (not shown in fig. 8), *Marginopora vertebralis*, and *Sorites marginalis*. All three species have long time ranges, from the Miocene into the present day at Enewetak, and cannot be used to subdivide these strata. The FAD of both *M. vertebralis* and *S. marginalis* is in the upper part of Zone LL (fig. 8); this Enewetak zone is placed in Zone NN 9 of early late Miocene age by Bybell and Poore (this volume).

Zones II-LL. These zones are of middle Miocene to early Pliocene ages. Several other larger foraminiferal species occur in these zones in addition to the three species mentioned above. They include three species of *Operculinoides*, two species of *Operculina*, and a single

species of *Alveolinella* and *Lepidocyclina*. These species are of limited biostratigraphic use over the western Pacific area.

Alveolinella quoyi has a FAD in the late middle Miocene and extends into the present-day western Pacific faunas, according to Adams (1984). This species has a much more restricted stratigraphic range in the Enewetak subsurface section; its lowest occurrence is in the middle of Zone LL, and it is eliminated in the lower part of Zone II (fig. 8) (uppermost middle Miocene to lower Pliocene). It does not occur in higher horizons in any Enewetak PEACE samples. A similar restriction of this species to older stratigraphic levels also was found in previous drill hole studies at Enewetak (Cole, 1957) and at Bikini (Todd and Post, 1954). This species is absent in present-day Enewetak assemblages and in those from other Marshall Islands studied by Cushman, Todd, and Post (1954). Thus, although the earliest Enewetak occurrence of this species is similar to the age given by Adams (1984) for the western Pacific, it has an early local extinction in the Marshall Islands.

Operculina lucidisutura is found in Zone II downward into middle Zone LL (fig. 8), or in the lower Pliocene to upper or upper middle Miocene Series. Cole (1957) reported the highest occurrence of this species at Enewetak from strata that he placed in Tg. The uppermost occurrence of *O. lucidisutura* in Zone II in the PEACE boreholes agrees with Cole's report; Zone II is assigned to the early Pliocene Epoch by Bybell and Poore (this volume); this assignment is where Adams (1984) places the base of Tg.

Operculina victoriensis is found sporadically in low abundances from lower Zone LL down into Zone MM (fig. 8), or in the middle Miocene to upper lower Miocene Series. Three species of *Operculinoides* occur in these zones. These three species are part of a grouping that exhibits considerable morphologic variation, particularly in the amount of test inflation. *O. rectilata* is found from Zone II down into Zone KK (fig. 8), or in the lower Pliocene down into the upper Miocene Series. Cole (1957) gave an upper limit of Tg for this species (Pliocene according to Adams, 1984); this assignment is in agreement with the highest occurrence in Zone II found here. *O. amplicuneata* is found from Zone JJ down into middle Zone LL (fig. 8), or in the upper Miocene to possibly uppermost middle Miocene Series. Cole (1957) reported a highest occurrence of this species at Enewetak in strata that he assigned to Tg (Pliocene, according to Adams, 1984); the occurrence here only in Miocene strata in KBZ-4 (fig. 6) and KAR-1 (fig. 7) suggests an upper limit in the upper part of Tf. The third species, *O. bikiniensis*, occurs only in lower Zone LL strata and is discussed below.

BOREHOLE	SAMPLE DEPTH (FEET) bsf	TAXA										ENEWETAK BENTHIC ZONE	TERTIARY FAR EAST LETTER ZONES
		<i>Lepidocyclina orientalis</i>	<i>Miogypsina thecidaceiformis</i>	<i>Lepidocyclina sumatrensis</i>	<i>Austrotrillina striata</i>	<i>Cyclocypeus transiens</i>	<i>Miogypsinoidea dehaartii</i>	<i>Spiroclypeus margaritatus</i>	<i>Miogypsinoidea ubaghsi</i>	<i>Heterostegina borneensis</i>	<i>Lepidocyclina ephippoides</i>		
OBZ-4	815	F										LOWER LL	Tf
	819		R									MM1	UPPER Te?
	828		F	F									
	834		R										
	873			C	A	R	A						
	892			R	A		R					MM2	UPPER Te
	900				A								
	909				C								
	912				C								
	924				A								
	933			A			A						
	964		A	C				A					
	1014			F			A						
	1046			F			A						
	1057			A			A						
	1067			A			A						
	1079			F			R	R					
	1086			F									
	1126			A				C					
	1130			F									
	1140			C				C					
	1146							A					
	1160							A					
	1190			R			R						
	1195						R						
	1211			F				F	A			MM3	LOWER Te
	1218		A						C				
	1226		R						R				
	1236		A						A				
	1249		A						A				
	1255		A						C				
	1289		A					F	A				
	1300		A					F					
	1338		R					A					
	1354		R					C					
	1383		A					F					
	1396		R										
	1402		R							A			
	1422		C							A			
	1428		F							C			
	1435		A							F			
	1447		R							F			
	1456		A							F			
	1465		A							C			
	1482									C			
	1493									C			
	1501												
	1513			R						R			
	1543									A	A		

FIGURE 4. — Occurrences of larger foraminiferal species and *Austrotrillina* in borehole OBZ-4 and placement in Enewetak benthic zones and Tertiary Far East Letter Zones. A=greater than 12 specimens; F=9-12 specimens; C=5-8 specimens; R=1-4 specimens. bsf, below sea floor.

BOREHOLE	SAMPLE DEPTH (FEET) bsf	TAXA					ENEWETAK BENTHIC ZONE	TERTIARY FAR EAST LETTER ZONES
		<i>Lepidocyclus orientalis</i>	<i>Lepidocyclus sumatrensis</i>	<i>Cyclopygeus transiens</i>	<i>Miogypsina thecideaformis</i>	<i>Miogypsinoides dehaartii</i>		
OOR-17	930	F	R				LOWER LL	Tf
	941		R	R	R		MM1	UPPER Te?
	959					R	MM2	UPPER Te
	989		R					
	1004		F					
	1025		F			R		
	1048		R			A		
	1054		R			A		
	1068					R		
OAR-2	884		F		R		MM1	UPPER Te?
	886		F		R			

FIGURE 5.—Occurrences of larger foraminiferal species in boreholes OOR-17 and OAR-2 and placement in Enewetak benthic zones and Tertiary Far East Letter Zones. A=greater than 12 specimens; F=9–12 specimens; C=5–8 specimens; R=1–4 specimens. bsf, below sea floor.

Lepidocyclus (*Nephrolepidina*) *orientalis*, the stratigraphically youngest ranging species of this genus in the subsurface of Enewetak, occurs only in the lowest 10 to 15 ft of lower Zone LL (fig. 8) in boreholes OBZ-4, KBZ-4, KAR-1, and OOR-17 (figs. 4–7). Cole (1957) also found this species to be confined to a 10-ft interval in the K-1B drill hole at Enewetak, which he considered to be the lowest part of Tf. Lower Zone LL of the PEACE boreholes is placed in Tf, but it is uncertain where in the middle Miocene this zone belongs.

Operculinoides bikiniensis co-occurs with *L. orientalis* in the lowermost part of Zone LL (fig. 8) in KBZ-4 and KAR-1 (figs. 6 and 7); *O. bikiniensis* is found only in these two PEACE coreholes, both located in KOA crater area, and only in samples that also contain *L. orientalis*. Cole (1957) considered that these two species were characteristic of the Tf zone; Adams (1970) also confined the range of *L. orientalis* to within Tf. Thus, the co-occurrence of these two species in lower Zone LL in the two PEACE boreholes suggests a placement of these strata within Tf, although it is uncertain in what portion of Tf they belong. Adams (1984) gave an age range of late early Miocene into the early Pliocene for Tf. A more

restrictive age range for the lower part of lower Zone LL strata to somewhere within the middle Miocene is suggested by the occurrence in these strata in several PEACE boreholes of planktic foraminifers and calcareous nannofossils that are characteristic of planktic foraminiferal Zones N 9 to N 13 (Bybell and Poore, this volume).

Zone MM. Zone MM was defined by Cronin and others (1986) to include all strata from the base of Zone LL to the bottom of the five deepest PEACE boreholes (KAR-1, KBZ-4, OAR-2 and 2A, OOR-17, and OBZ-4), which penetrated strata below Zone LL. No datable calcareous nannofossils or planktic foraminifers were recovered from definite Zone MM. Well-preserved smaller foraminifers and ostracodes are present in the upper part of Zone MM, where they were used to delineate this zone from Zone LL, but these groups are highly recrystallized and unidentifiable in the middle and lower parts of this zone. However, most parts of Zone MM contain abundant and well-preserved larger foraminiferal specimens.

The LL–MM zonal boundary is placed at 815 ft in OBZ-4 and here coincides with unconformity number 7 of Wardlaw and Henry (1986). Unconformity 7 of Wardlaw and Henry (1986) is coincident with the LL–MM boundary in four of the five boreholes. The base of Zone LL is marked in the larger foraminifers by the FAD of *L. (Nephrolepidina) orientalis* and *O. bikiniensis*; the top of Zone MM is marked by the LAD of *Miogypsina (Lepidosemicyclina) thecideaformis* and *Lepidocyclus (Nephrolepidina) sumatrensis* (fig. 8). Zone MM can be divided into subzones MM1, MM2, and MM3 on the basis of the stratigraphic distribution of the larger foraminiferal assemblages. The new foraminiferal subdivisions of Zone MM and their characteristic larger foraminiferal assemblages are as follows.

Subzone MM1. This subzone is marked by the presence of *Miogypsina (Lepidosemicyclina) thecideaformis*. The top of Subzone MM1 is marked by the local extinction of *M. (Lepidosemicyclina) thecideaformis* and *Lepidocyclus (Nephrolepidina) sumatrensis* and by the FAD of *L. orientalis* and *O. bikiniensis* in the overlying lowermost part of lower Zone LL (fig. 8). The normal first appearance of *M. (Lepidosemicyclina) thecideaformis* marks the base of the subzone, and the local extinction of *Miogypsinoides (Miogypsinoides) dehaartii* occurs at the top of the underlying Subzone MM2 (an exception to this pattern is found in one sample at 964 ft in OBZ-4, where *M. thecideaformis* and *M. dehaartii* both occur). Cole (1957, p. 746) recognized a sequence of species occurrences similar to that found in the Bikini drill holes. Subzone MM1 extends from 815 to 834 ft in OBZ-4.

BOREHOLE	SAMPLE DEPTH (FEET) bsf	TAXA										ENEWETAK BENTHIC ZONE	TERTIARY FAR EAST LETTER ZONES	
		<i>Operculina lucidisutura</i>	<i>Operculinoides rectilata</i>	<i>Operculinoides amplicuneata</i>	<i>Marginopora vertebralis</i>	<i>Alveolinella quoyi</i>	<i>Sorites marginalis</i>	<i>Lepidocyclina orientalis</i>	<i>Operculina victoriensis</i>	<i>Operculinoides bikiniensis</i>	<i>Lepidocyclina sumatrensis</i>			<i>Miogypsina thecideaformis</i>
KBZ-4	521	F											II	Tg
	555	F	F											
	561	R	R											
	565	R	F											
	569	R	F										JJ	Tf
	592	R		R										
	665	F												
	674				R									
	719	F		R										
	728	R				R	R						KK	
	756	F				R								
	760	R		R	R									
	765	R		R	R									
	777	A		A	A								UPPER LL	
	780	C		A	R	F								
	812	R		F										
	829			R			R							
	855							R	R	A				
	860							C		A				
	864							F	R	R				
	915										F		MM1	UPPER Te?
	925											C		
	930											A		
	935										R			
	949								F		R		MM2	UPPER Te
	972											A		
976										R				
980										F				
996										R				
1041											C			
1045											F			

FIGURE 6.—Occurrences of larger foraminiferal species in borehole KBZ-4 and placement in Enewetak benthic zones and Tertiary Far East Letter Zones. A=greater than 12 specimens; F=9–12 specimens; C=5–8 specimens; R=1–4 specimens. bsf, below sea floor.

Both *M. (Lepidosemicyclina) thecideaformis* and *L. (Nephrolepidina) sumatrensis* are known to range from upper Te into the lower part of Tf (Adams, 1970; Cole, 1975; Chaproniere, 1984, found *M. thecideaformis* extending as high as Zone N 9 in Tf strata in Australia); Subzone MM1 is tentatively placed in upper Te, however, as upper Te is the most common time of overlap of these two species and species commonly present in Tf, such as *L. (Nephrolepidina) orientalis*, are absent from the assemblages. *Cycloclypeus transiens* occurs in one sample in Subzone MM1 and in one sample in the uppermost part of Subzone MM2; Cole (1975) reported this species from upper Te and Tf in the western Pacific.

Subzone MM1 is present in the five deepest PEACE boreholes. The thickness of Subzone MM1 varies considerably in the different PEACE boreholes; much of this

variation may be an artifact of the absence of larger foraminiferal assemblages in some relatively thick intervals in the boreholes; this absence makes definitely placing the subzone boundaries difficult. Borehole OAR-2 reached into Subzone MM1 but did not penetrate into Subzone MM2, as the other four boreholes did.

Subzone MM2. This subzone is defined by the total range of *M. dehaartii*; it extends from 873 to 1,195 ft in OBZ-4. The lower part of Subzone MM2 in OBZ-4, from 1,079 to 1,195 ft, is characterized by the co-occurrence of *Spiroclypeus margaritatus*, *M. dehaartii*, and *L. sumatrensis*.

Subzone MM2 is present in the four deepest PEACE boreholes, and it was recognized also by examination of the occurrences in Cole's (1957) data from Enewetak drill holes K-1B, E-1, and F-1. Borehole OBZ-4 penetrated

BOREHOLE	SAMPLE DEPTH (FEET) bsf	TAXA											ENEWETAK BENTHIC ZONE	TERTIARY FAR EAST LETTER ZONES	
		<i>Operculinoides rectilata</i>	<i>Operculina lucidisutura</i>	<i>Alveolinella quoyi</i>	<i>Marginopora vertebralis</i>	<i>Sorites marginalis</i>	<i>Operculinoides amplicuneata</i>	<i>Lepidocyclina orientalis</i>	<i>Operculinoides bikiniensis</i>	<i>Lepidocyclina sumatrensis</i>	<i>Miogypsina thecideaformis</i>	<i>Operculina victoriensis</i>			<i>Miogypsinooides dehaartii</i>
KAR-1	537	R											II	Tg	
	539	R													
	542	R													
	549	R	R												
	552	R	R												
	555	R													
	584	A	R	R	A	R									
	590	A	R	F	A	R									
	591	A	R	F	A	R									
	592	C	R	F	A	R									
	670				R								JJ	Tf	
	702				R										
	723			F	R								KK		
	727			F											
	736	R		R	R										
	744	A		F											
	754		R	R	R								UPPER LL		
	795			R	R	F									
	804		R	R	R	F									
	817		R	R	R		R								
	822		R	R	R	F	C						MIDDLE LL		
	829		R	R	R		R								
	873		R	R	R		C								
	876						C								
	920							A	C				LOWER LL		
	924							C	R						
	927														
	980									F					
	986										F		MM1	UPPER Te?	
	991									R	R				
	1004										A				
	1012									R		C			
	1136									R			MM2	UPPER Te	
	1140											R			
	1146											R			

FIGURE 7.—Occurrences of larger foraminiferal species in borehole KAR-1 and placement in Enewetak benthic zones and Tertiary Far East Letter Zones. A=greater than 12 specimens; F=9–12 specimens; C=5–8 specimens; R=1–4 specimens. bsf, below sea floor.

through Subzone MM2 and into Subzone MM3; boreholes OOR-17, KBZ-4, and KAR-1 penetrated into Subzone MM2 but not deeply enough to reach the interval of *S. margaritatus* in the lower part of MM2.

The coincidence of the last appearance of both *M. dehaartii* and *Austrotrillina striata* (a smaller benthic species) at 873 ft in OBZ-4 suggests a possible hiatus at or slightly above this horizon. Unconformity number 8 of Wardlaw and Henry (1986) occurs at 866 ft in OBZ-4; this horizon may more accurately represent the last appearance of these two species because the next sample studied above 873 ft is from above this unconformity.

The concurrent ranges of *M. dehaartii* and *L. sumatrensis* from 873 to 964 ft in OBZ-4, and the presence of *A. striata* from 873 to 924 ft, suggest placement of upper Subzone MM2 into upper Te (Adams, 1970, 1984; Chaproniere, 1984). These authors assign upper Te from the Oligocene-Miocene boundary to the middle lower Miocene (from within planktic foraminiferal Zone N 4 to within Zone N 6).

The lower part of Subzone MM2 below 1,079 ft in OBZ-4 also is assigned to upper Te (lower Miocene). The co-occurrence here of *M. dehaartii*, *L. sumatrensis*, and *S. margaritatus* suggests that this part of Subzone MM2

borneensis was considered by Haak and Postuma (1975) to mark the top of lower Te, and both species occur in Subzone MM3.

SMALLER FORAMINIFERAL OCCURRENCES AND AGE ASSIGNMENTS

Diagenetic alteration of smaller benthic foraminiferal tests occurs in several stratigraphic intervals of the PEACE boreholes; this alteration presents problems in species identifications and thus in the determination of biostratigraphic ranges of some of these taxa. Alteration is most extensive in much of the lower strata (late Oligocene and early Miocene age), where essentially all smaller foraminiferal species are either so badly recrystallized as to be unidentifiable or have been completely removed by dissolution. Even in some intervals in the middle parts of the boreholes, particularly in Zone HH of Cronin and others (1986) (early Pliocene age), almost all smaller benthic species except for *Amphistegina* have been badly recrystallized and are generally unidentifiable.

Our examination of smaller benthic species distributions in the PEACE samples indicates that many species do have restricted biostratigraphic occurrences within Enewetak. Forty-nine smaller benthic foraminiferal species having short to moderately long local stratigraphic ranges were used to help subdivide the Holocene to Miocene strata into 13 biostratigraphic zones (Cronin and others, 1986). Although many of the Enewetak age ranges may be only of local significance, some species may have similar age ranges over much of the western Pacific area and are useful biostratigraphically. However, biostratigraphic ranges for most smaller benthic foraminiferal species found in the Enewetak samples are largely unknown for the western Pacific area. Many of the earlier species reports have broad or vague age ranges applied to them, and so the species are difficult to place into a refined biostratigraphic age.

A lack of biostratigraphic control for smaller benthic species is suggested by the earliest appearance of many smaller benthic species of the Pacific basin in the Enewetak subsurface stratigraphic sections (Gibson, 1987). How many of these earliest appearances at Enewetak can be applied to the Pacific basin as FAD's is uncertain. Whether the large numbers of earliest occurrences at Enewetak are an artifact of the intensive sampling done in the numerous cores at Enewetak or whether this part of the western Pacific is the actual area of origination of many of these species still is uncertain. However, the biostratigraphic information presently available in the foraminiferal literature suggests that many of these species did originate in the western Pacific.

Adams (1984, fig. 5) gave, in addition to age ranges of larger foraminiferal species, the age ranges of several Indo-West Pacific smaller benthic foraminiferal species that he considered possibly useful biostratigraphically. Three of these taxa from Adams' study, *Baculogypsina sphaerulata*, *Calcarina spengleri*, and *Austrotrillina striata*, occur in the Enewetak samples. Their stratigraphic ranges at Enewetak and at other islands in the Marshalls are given here for comparison with their overall Pacific ranges.

Baculogypsina sphaerulata.—Adams (1984) reported this species as ranging from the base of the Pleistocene Series (base of Calabrian age) into the present-day faunas in the Indo-Pacific area. Its stratigraphic range in Enewetak strata is considerably shorter, as it occurs there only in Zone CC of Cronin and others (1986). Zone CC is above the base of the Pleistocene Series, which is placed within Zone EE–FF at Enewetak (Bybell and Poore, this volume); thus, this species has a later FAD at Enewetak than in some other Pacific locations. It also exhibits an older LAD at Enewetak, as it is not found in the upper Pleistocene and Holocene strata in the cores (Zones AA and BB of Cronin and others, 1986). Todd and Post (1954) also reported a similar middle Pleistocene local extinction at Bikini. This species is not known from the living assemblages at Enewetak or throughout the entire Marshall Islands (Cushman, Todd, and Post, 1954), even though it still is living in other parts of the western Pacific.

Calcarina spengleri.—Adams (1984) recorded this species from basal Pleistocene strata, with questionable occurrences extending into the middle Pliocene, into the present-day fauna. This species has a similar stratigraphic distribution in the PEACE cores; *C. spengleri* is the overwhelmingly dominant species in the Holocene (Zone AA) foraminiferal assemblages from the shallow back-reef environments. This species is rare and sporadic in the older zones and extends to the middle to upper parts of Zone EE of Cronin and others (1986) (latest Pliocene to basal Pleistocene age, according to Bybell and Poore, this volume).

Austrotrillina striata.—The smaller benthic genus *Austrotrillina* has been incorporated into western Pacific biostratigraphic zonations by Adams (1984) and Chaproniere (1984). Two species, *A. striata* and *A. houchini*, commonly are integrated into larger foraminiferal biostratigraphic zonations and used as characteristic species of the TFELZ in the western Pacific. *A. striata* occurs in middle and upper Oligocene through lower Miocene strata, or approximately upper Zone P 19 to Zone N 6 (planktic foraminiferal zones of Blow, 1969), according to Adams (1984). Chaproniere (1984) gives an earlier extinction in Australia at the top of Zone N 4. This species is considered characteristic of uppermost Td

through Te (both lower and upper Te) letter zones. *A. howchini*, which is characteristic of the lower part of Tf, occurs in upper lower and lowermost middle Miocene strata, most commonly in Zones N 7 and N 8, but ranges from Zone N 6 to within Zone N 9 (Chaproniere, 1981, 1984; Adams, 1984). Only the older of these two species, *A. striata*, has been recognized in the PEACE boreholes.

Austrotrillina striata is found in only one of the PEACE boreholes, OBZ-4, in samples from depths of 873 to 924 ft. Below 924 ft, smaller benthic foraminifera are unrecognizable because of recrystallization. This species is absent from equivalent intervals in boreholes KBZ-4 and OOR-17, presumably because of significant recrystallization of the microfaunas at these depths in the two boreholes. No planktic foraminifers or calcareous nannofossils were recovered from the interval containing *A. striata* in OBZ-4. The sample at 808 ft, which was placed within Zones N 9-13 (middle Miocene) on the basis of planktic foraminifers (Bybell and Poore, this volume), is 65 ft above the highest occurrence of *A. striata* in OBZ-4. Adams (1984) considered that the highest occurrences of *A. striata* are usually within Zone N 6.

The fairly close proximity in depth between presumably middle lower Miocene and middle Miocene strata in OBZ-4 suggests that sediment accumulation during some of late early and early middle Miocene Epoch may be missing here; if the middle Miocene strata are only from the higher part of this zonal range of N 9 to N 13, much of the middle Miocene may be missing at Enewetak. The possible absence of Zones N 7 and N 8 age strata in OBZ-4 and in the other Marshall Island drill holes may explain the absence of *A. howchini*, which commonly occurs in these zones in other western Pacific areas (Adams, 1984). Ecological factors may provide an alternative explanation for this absence of *A. howchini* in the Marshall Islands, but this explanation seems unlikely because similar, shallow back-reef environments are characteristic of the lower to middle Miocene strata in the boreholes. The specimens reported from Enewetak and Bikini as *A. howchini* (Cole, 1954; Todd and Post, 1954; Todd and Low, 1960) were examined subsequently by Adams (1968) and placed into *A. striata*.

Austrotrillina striata also is found at Enewetak in deep drill hole E-1 (fig. 1) (Todd and Low, 1960), where it occurs abundantly in cuttings between 1,835 and 2,003 ft and in core sample E-1-1-1 from 2,003-2,028 ft. On the basis of the presence of this genus, Cole (1957) placed this cored interval into the lower part of Te. Cole also found larger foraminiferal species typical of lower Te (*Heterostegina borneensis* and *Lepidocyclina* (*Eulepidina*) *ephippioides*) at similar depths (and therefore presumably a similar stratigraphic position) in another drill hole, F-1, at Enewetak; their presence supports this

assignment to lower Te. Sample E-1-1-1 contains *Globorotalia kugleri* (Bybell and Poore, this volume) and thus is of latest Oligocene or earliest Miocene age; the associated calcareous nannofossils suggest a possible Oligocene placement of these strata, which is in agreement with the lower Te assignment.

RATES OF ACCUMULATION

Rates of accumulation at Enewetak during the late Oligocene to Holocene are estimated from drill hole biostratigraphic data. Two data sources are available; middle Miocene to Holocene biostratigraphic data from middle and upper parts of the PEACE boreholes (Cronin and others, 1986; Bybell and Poore, this volume) and upper Oligocene and lower Miocene foraminiferal data from the lower part of the PEACE boreholes (this study).

The shallowest depth of species occurrences in the PEACE boreholes, as given in Cronin and others (1986), is referenced to the beginning point of drilling on the sea bottom at each site. PEACE borehole sites were all located below sea level; previous deep drill hole sites at Enewetak were on land. To compare biostratigraphic events from all these data sets, sample depths need to be standardized to depths below sea level (fig. 2).

Following normalization to depth below sea level, depth differences of considerably less than 100 ft generally are found for equivalent biostratigraphic horizons among the various Enewetak drilling sites. These depth differences are relatively small in relation to the considerable thickness of upper Oligocene and lower Miocene strata found at Enewetak and do not significantly affect the general thickness patterns. The depth differences in many cases may result more from the difficulty of finding species in sparse assemblages or the presence of nonfossiliferous intervals rather than from an actual difference in the LAD's. Differences in the depth of equivalent horizons in relation to sea level also may exist in the various drill holes because of erosional relief developed on the limestone surfaces on which they were deposited.

The placement of subzones MM1 and MM2 in the early Miocene demonstrates that a considerable sedimentary thickness accumulated during this time interval. Subzone MM2 is considered to have a maximum time extent from the beginning of the Miocene (Zone N 4) to the end of the time range of *Austrotrillina striata* (top of Zone N 6), or about 7 m.y. (Haq and others, 1987). The accumulation of approximately 340 ft of sediment in borehole OBZ-4 during this subzone yields an accumulation rate of nearly 50 ft/m.y. during this part of the early Miocene. The addition of approximately 60 ft of lower Miocene subzone MM1 gives a thickness of about 400 ft for early

Miocene sedimentation. This thickness compares with a thickness of about 1,000 ft for the middle Miocene to Holocene strata in OBZ-4 (to sea level); these strata represent a time span of as little as 11 m.y. or as many as 15 m.y., depending upon where, in the Zone N 9 to Zone N 13 range, the sediments in the lower part of Zone LL belong. These age variations yield an accumulation rate of a minimum of 65 to a maximum of 90 ft/m.y.; the minimum rate is slightly greater than that calculated for the early Miocene, and the maximum rate is almost twice as great.

The top of Zone MM3, a zone herein considered to belong in lower Te and thus to be of late Oligocene age, is at a depth of 1,409 ft bsl in borehole OBZ-4. The lowermost sample dated in this borehole, at 1,742 ft bsl, still is placed in lower Te. This placement shows a minimum upper Oligocene thickness of 332 ft in OBZ-4. A late Oligocene sedimentation rate cannot be calculated from this borehole alone, however, because the exact placement in the late Oligocene for the lowermost strata is unknown; thus, the amount of time that these strata represent also is unknown.

Although the total thickness of upper Oligocene strata at Enewetak is uncertain, a minimum of slightly greater than 300 ft is present; the documentation herein of this thickness of upper Oligocene and approximately 400 ft of lower Miocene demonstrates that the late Oligocene and early Miocene are major times of accumulation at Enewetak. As the thickness of carbonate sediments in atolls appears to be limited largely by the rate of subsidence, the thickness suggests that these intervals were also times of significant subsidence.

Accumulation rates of 50 to 90 ft/m.y. are estimated in the present study for the lower Miocene and the middle Miocene to Holocene strata at Enewetak. These rates are similar to those proposed by Schlanger and others (1987), who calculated subsidence rates of 82 to 98 ft/m.y. for the Marshall Island area from the study of drowned atolls there.

LIST OF SPECIES TREATED FROM PEACE AND EXPOE ENEWETAK SUBSURFACE SAMPLES

LARGER FORAMINIFERS

Alveolinella quoyi (d'Orbigny)
Cycloclypeus transiens Tan
Heterostegina borneensis van der Vlerk
Heterostegina suborbicularis d'Orbigny
Lepidocyclus (*Eulepidina*) *ephippioides* Jones and Chapman
Lepidocyclus (*Nephrolepidina*) *orientalis* van der Vlerk
Lepidocyclus (*Nephrolepidina*) *sumatrensis* (Brady)

Marginopera vertebralis Quoy and Gaimard
Miogypsinoides dehaartii (van der Vlerk)
Miogypsinoides (*Lepidosemicyclina*) *thecideaeformis* (L. Rutten)
Miogypsinoides ubaghsi Tan
Operculina lucidisutura Cole
Operculina victoriensis Chapman and Parr
Operculinoides amplicuneata Cole
Operculinoides bikiniensis Cole
Operculinoides rectilata Cole
Sorites marginalis (Lamarck)
Spiroclypeus margaritatus (Schlumberger)

SMALLER BENTHIC FORAMINIFERS

Austrotrillina striata Todd and Post
Baculogypsina sphaerulata (Parker and Jones)
Calcarina spengleri (Gmelin)

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