39. PLANKTONIC MICROFOSSIL BIOSTRATIGRAPHY OF THE NORTHWESTERN PACIFIC OCEAN

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INTRODUCTION

Biostratigraphic evidence obtained from the northwestern Pacific Ocean as a result of coring carried out by the *Glomar Challenger* during Leg 6 of the Deep Sea Drilling Project from Hawaii to Guam is considered here mainly from the standpoint of three dominant marine planktonic microfossil groups—calcareous nannoplankton, foraminifers, and radiolarians. The co-occurrence of these microfossils in various types of sediment in 684 meters of core recovered along a 9000-kilometer traverse of the Pacific (Figure 1) provides the opportunity to compare zonal units, paleoecology, preservation, correlation to land sections, and variation in sedimentation rates as determined by these fossil groups.

A comparison of zonal units of calcareous nannoplankton, foraminifera, and radiolarians in the same strata shows only few cases of exact coincidence of zonal limits, especially if coincidences at the top or bottom of the standard 9-meter coring runs are dismissed as artificially induced owing to gaps in sediment recovery. Exact coincidence of zonal limits within coring runs are most notable for the Upper Paleocene sediment of the Shatsky Rise, where the *Heliolithus kleinpelli* Zone (nannoplankton) is equivalent to *Globorotalia pseudomenardii* Subzone (foraminifera), the *Heliolithus riedeli* Zone (nannoplankton) to *Globorotalia velascoensis* Zone (foraminifera), and the *Discoaster multiradiatus* Zone (nannoplankton) to *Globorotalia subbotinae* Zone (foraminifera). A significant example of noncoincidence occurs at the Cretaceous-Tertiary boundary of the Shatsky Rise. Although both calcareous nannoplankton and planktonic foraminifera underwent profound extinctions and rejuvenation near this boundary worldwide, evidence from our coring indicates that the great

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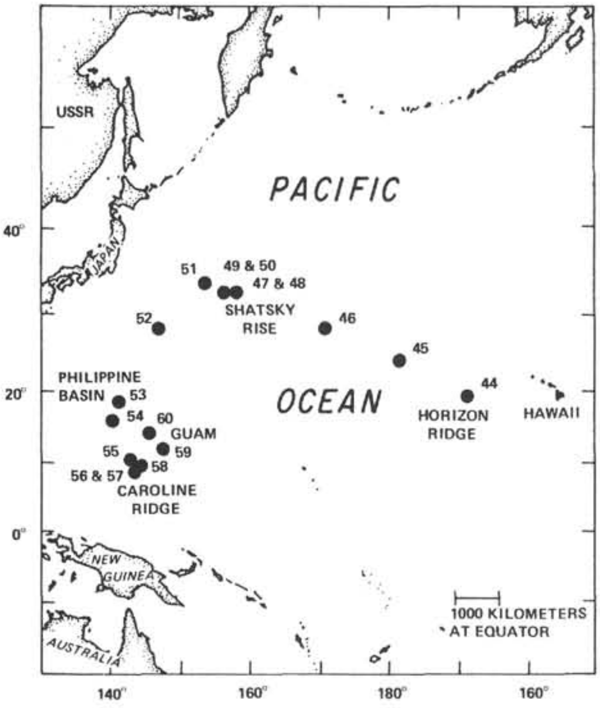


Figure 1. *Location of drilling sites in the northwestern Pacific Ocean, Deep Sea Drilling Project, Leg 6.*

change in assemblages of planktonic foraminifera occurred before that of the calcareous nannoplankton. The uppermost Maestrichtian *Tetralithus murus* Zone (nannoplankton) is recognized in samples that contain foraminiferal assemblages dominated by species representing the lowermost Danian *Globigerina taurica* Zone and *Globorotalia trinidadensis* Zone of foraminifera.

Interpretation of zonal and paleoecologic data intimately involves consideration of the effects of preservation of microfossils. In general, sediment containing all three microfossil groups has been little effected by dissolution. For the two main types of dissolution resulting from a great water depth during deposition, planktonic foraminifera are completely removed, whereas the calcareous nannoplankton and radiolarians are either represented only by resistant species or only the most resistant radiolarians remain. In calcareous oozes deposited at moderate depths, calcareous nannoplankton, especially the star-shaped discoasters, are overgrown with secondary calcite. The siliceous radiolarians are absent from several of our shallow carbonate ooze samples, suggesting strong dissolution control of radiolarian assemblages in relatively shallow ooze. Whereas planktonic foraminifera and calcareous nannoplankton show many degrees of preservation, owing to a range of overgrowths and dissolution of individual specimens, radiolarians do not show evident signs of such alteration. The state of preservation of radiolarian assemblages is mainly indicated by the number of taxa present that are least resistant to solution. Following complete dissolution of less-resistant taxa, specimens of more-resistant taxa are not noticeably altered.

Paleoecologic biogeographic patterns are best represented by radiolarians, which exhibit a much greater distinction in species composition between assemblages from our northern and southern sites than do the calcareous nannoplankton and planktonic foraminifera. Nannoplankton assemblages from the open ocean areas investigated are distinctly smaller in number of species than nearshore and basin assemblages of the same age.

A comparison of the biostratigraphic data accumulated during Leg 6 with studies of outcrop sections in the Circum-Pacific region and Pacific islands demonstrates that few studies have attempted to correlate through the Pacific region. The micropaleontologic content of sediment sections cored by the Deep Sea Drilling Project provides a basis for comparison of taxonomic, paleoecologic, and preservational relations that can initiate a synthesis of the geologic history of the vast Pacific realm.

ZONAL COMPARISON

Series boundaries are based on certain stage boundaries where major changes in megafossil assemblages occur. These major boundaries were established originally in sections of shelf and nearshore marine sediment cropping out on land. The correlation of zones of planktonic open-ocean microfossils to these type stages often is presumptive because the lithologic facies of these stages in type areas do not necessarily include such microfossils. Therefore, using diverse lines of evidence and reasoning, workers studying planktonic microfossils have developed various concepts of series boundaries that are based on particularly significant zonal changes for their groups. Leg 6 cores provide a basis for a comparison of series boundaries determined from a variety of fossil groups.

Comparison of zonal scales based on nannoplankton, Radiolaria, and planktonic foraminifera shows generally close coincidence of boundaries of zonal subdivisions. Some discrepancies are accounted for mainly by a gradual change of faunas and floras at boundaries of stratigraphic units. Uninterrupted and high sedimentation rates often serve to magnify zonal boundaries and lead to the recognition of transitional sequences not represented in zones known from type stages. Partly, the discrepancies are the result of different understanding of the essence of zones (chronostratigraphic zones of intercontinental extent or biostratigraphic provincial and local zones).

Comparatively more significant discrepancies are observed with respect to understanding stratigraphic units of higher rank (stage, subseries, series). These may result in part from general shortcomings of the international stratigraphic scale, owing to such factors as unconformities and reinterpretations of paleontologic evidence.

In sediment cores from several drilling sites, the cooccurrence of abundant assemblages of foraminifera and nannoplankton, commonly also with radiolarians, allows a comparison within the same strata of zonal boundaries and series boundaries based on these groups (Figure 2). This comparison allows assessment of the potential for combination zones based on changes in assemblages of two or more groups and assessment of the relative control of environmental factors on the microfossil groups.

The method of nannoplankton zonation, like that used for foraminifera, does not rely solely on first or last occurrences of single species, but instead takes into account the overall aspect of the changes occurring within the assemblages. Radiolarian zonation is keyed more closely to the ranges of individual species.

For sediment of Maestrichtian, Paleocene, Eocene, and early Oligocene age, one can compare the zonal scales based on foraminifera and nannoplankton. In late Oligocene and younger sediment, these groups of fossils as a rule are accompanied by radiolarians, due to preservational factors. Here, analysis and comparison of zonal scales can be based on planktonic foraminifera, radiolarians, and nannoplankton.

Upper Cretaceous-Paleocene Boundary

The most striking boundary for the nannoplankton assemblages is that between the Tertiary and Cretaceous (Danian and Maestrichtian). A sedimentary interval including this boundary was cored at the Shatsky Rise, Hole 47.2, Core 11. Bramlette and Martini (1964) published a detailed study of the worldwide Danian-Maestrichtian boundary in which they demonstrated an almost complete extinction of Cretaceous nannoplankton genera and species. A similar dramatic change is present in the Shatsky Rise material, but the tentative basal Paleocene nannoplankton *Markalius astroporus* Zone is not present. Instead *Cruciplacolithus tenuis* is present in the lowermost Paleocene samples examined, thus indicating the *C. tenuis* Zone. The question of whether the *M. astroporus* Zone in previously studied sections represents only an impoverished facies of the *C. tenuis* Zone (M. N. Bramlette, personal communication, 1968) or a distinct biostratigraphic unit must await further study; but the transitional nature of the Core 11 assemblages seems to argue against the presence of the *M. astroporus* Zone in deep-ocean sediment. The nannoplankton in the lower part of the core belong entirely to the latest Cretaceous *Tetralithus murus* Zone, whereas the upper part of the core contains species representing both the *T. murus* and *C. tenuis* Zones and is considered transitional Cretaceous-Tertiary.

According to foraminiferal faunas, Core 11 contains the lowermost Paleocene *Globorotalia trinidadensis* and *Globigerina taurica* Zones, with small numbers of species of the Upper Maestrichtian *Abathomphalus mayaroensis* Zone throughout, though more common in the bottom part of the core. Below this core, characteristic assemblages of the *A. mayaroensis* Zone occur with the uppermost Maestrichtian *Tetralithus murus* Zone of nannoplankton.

In detail, the identification of only late Maestrichtian nannoplankton in samples from the lower part of Core 11 (Sections 3, 4, 5 and 6), which contains foraminifera representative of early Danian and late Maestrichtian, indicates that the great evolutionary changes that affected these microfossils did not have a precisely synchronous effect. Tertiary planktonic foraminiferal species appeared before the calcareous nannoplankton species generally used to indicate the earliest Tertiary.

The authors have considered but tentatively rejected possible Paleocene mixing and mixing during drilling to explain the observed relations. Unmixed fine-grained nannoplankton occur with seemingly younger coarser-grained foraminifera, and this relationship cannot easily be obtained by simple mixing but could result if the foraminifera now considered Tertiary appeared prior to nannoplankton considered Tertiary. The missing record of transition in the type Danian (basal Tertiary) section, discussed by Bramlette and Martini (1964), appears to be represented in Core 11 from the Shatsky Rise. Discussion of the specific details of the transition will have to be deferred until close-interval samples are available. The initial studies show the widely recognized Upper Cretaceous nannoplankton taxa: *Arkhangelskiella cymbiformis, Cribrosphaera ehrenbergi, Cylindralithus gallicus, Eiffellithus turriseiffeli, Microrhabdulus decoratus, Prediscosphaera cretacea, Tetralithus murus* and *Watznaueria barnesae* occurring abundantly from Core 14 through the bottom of Core 11, Section 3; whereas from the top of Core 11, Section 3, through Sections 1 and 2 above, these older taxa gradually drop out, and the abundance of the remaining species is reduced, so that by the top of Section 1 only a few specimens of *A. cymbiformis, T. murus,* and *W. barnesae* remain. The only taxon of Cretaceous aspect recorded from Core 10 directly above is *W. barnesae.*

Within this same interval, nannoplankton taxa generally used to identify early Tertiary sediment first appear and increase in numbers and abundance to the top of Core 11. *Coccolithus pelagicus s.l., Coccolithus* sp. (small, single cycles), and *Cruciplacolithus tenuis* are

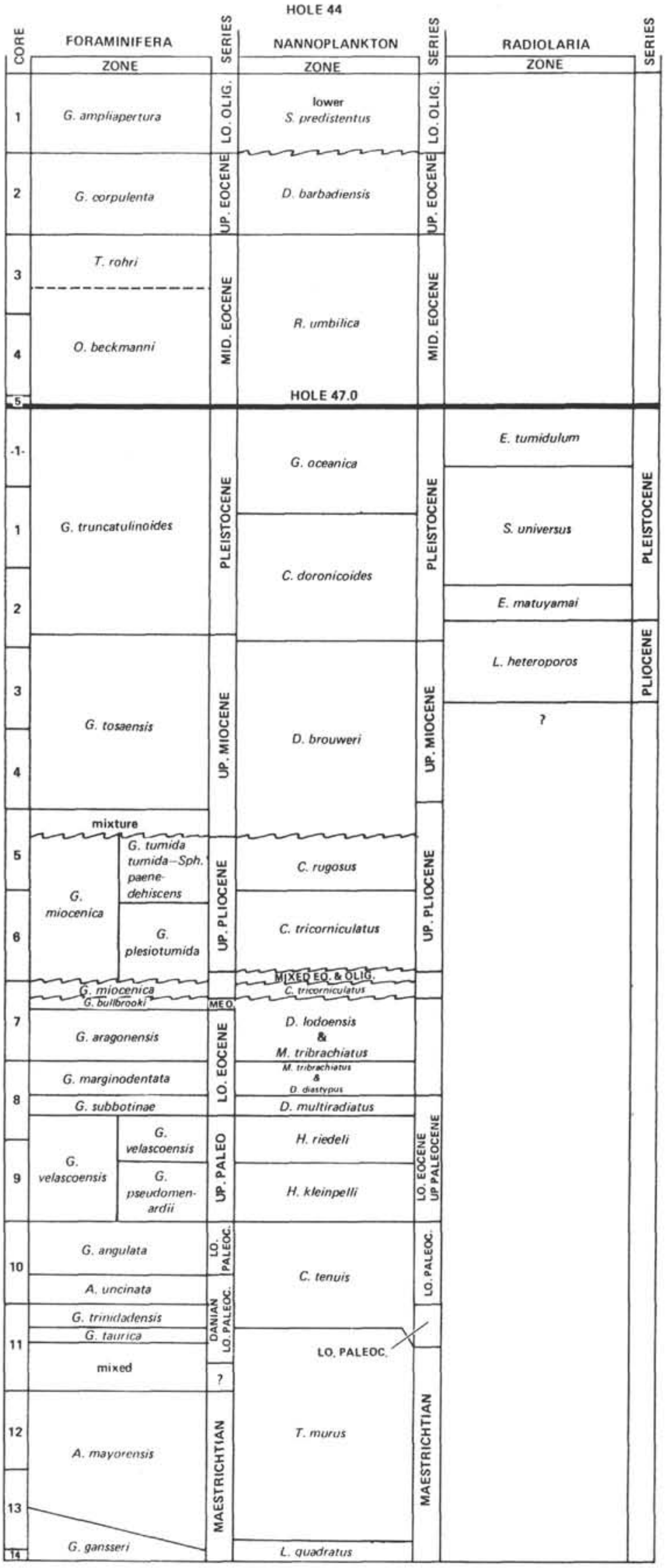


Figure 2. *Comparison of the limits of microfossil zones in Leg 6 cores, northwestern Pacific Ocean.*

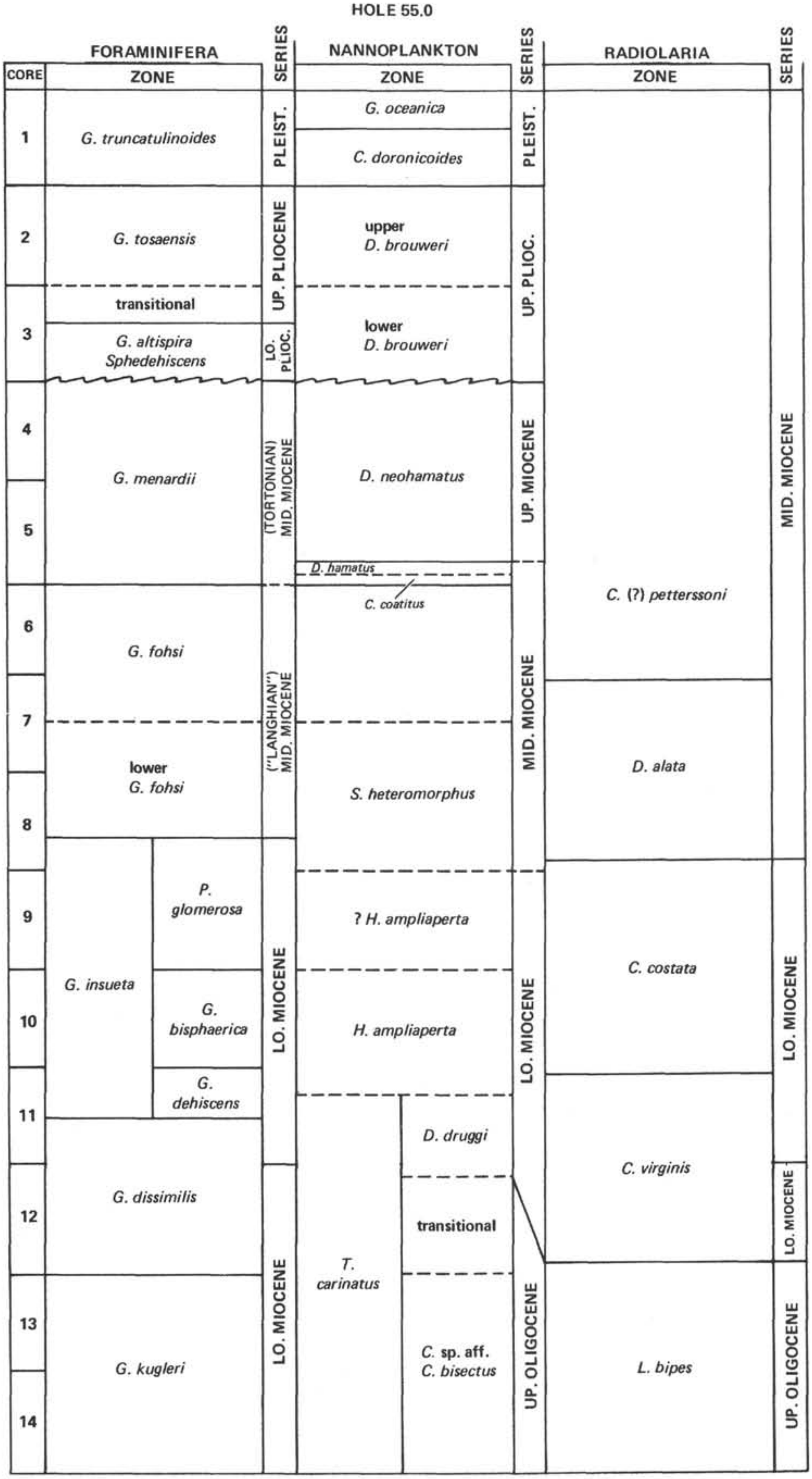


Figure 2. *(Continued)*

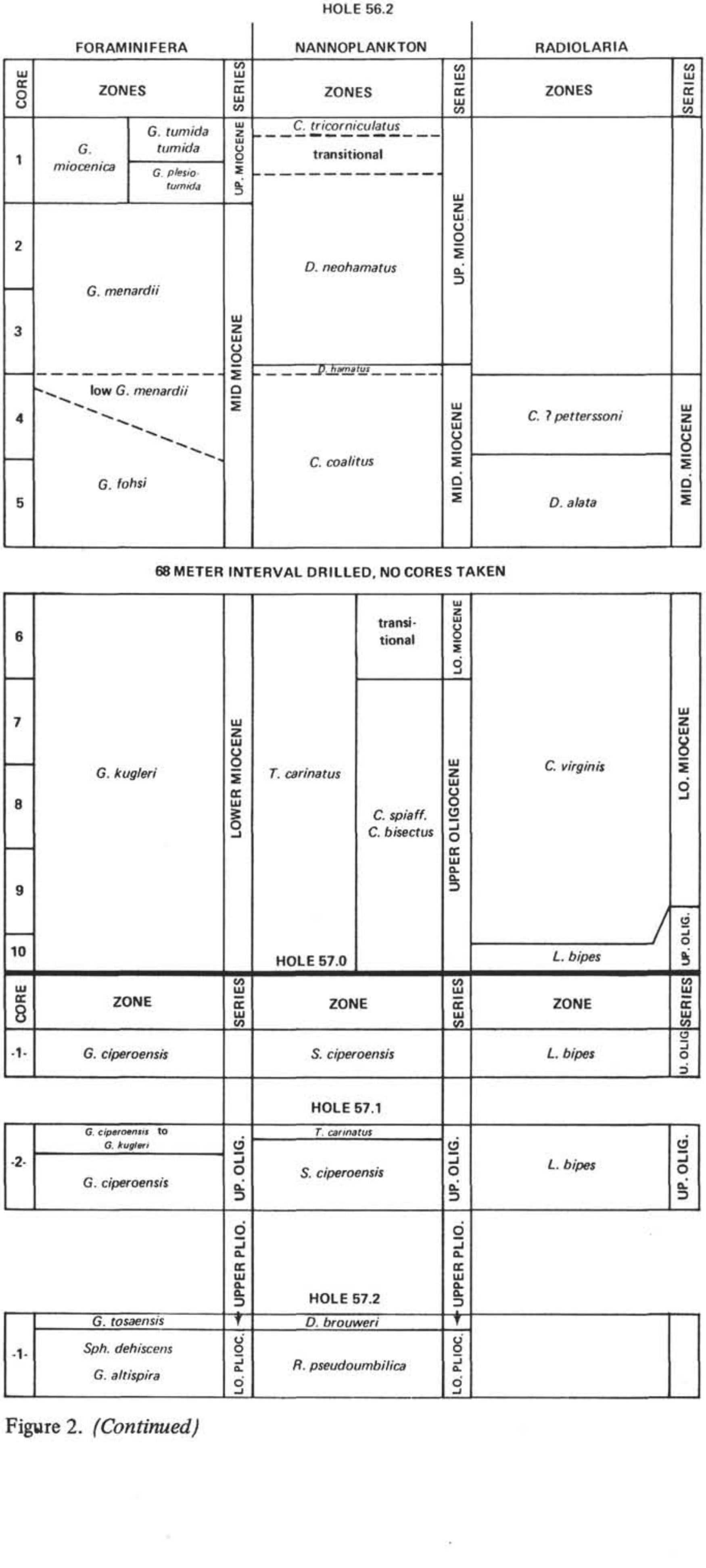


Figure 2. *(Continued)*

present at the top of Section 3, and *C. pelagicus s.l., C.* sp. (small, single cycles), *C. tenuis, Markalius astroporus,* and *Zygodiscus sigmoides* are present in Section 1. Other new taxa, such as, *Fasciculithus,* appear directly above in Core 10 and verify the Tertiary assignment of that core.

Foraminiferal taxa, such as, *Globigerina daubjergensis, G. eobulloides* and *G. pseudobulloides,* are considered to be basal Tertiary or transitional Cretaceous-Tertiary and occur throughout Core 11. Taxa considered to be Cretaceous, such as, *Abathomphalus mayaroensis, Globotruncana contusa, G. aegyptiaca* and *G. stuarti,* are present in small numbers in Sections 4 to 6 but greatly reduced in Sections 1 to 3 above. All of the Cretaceous specimens are chalky in appearance like those from Core 12 and probably represent minor reworking. The highest assemblages of nannoplankton and foraminifera definitely considered Cretaceous are separated by a 5-meter sediment interval that would represent approximately 400,000 years in view of the fossil preservation, thickness, and inferred time span for the Maestrichtian of the Shatsky Rise.

Reinterpretation of Cretaceous-Tertiary boundary sections in other areas may also show that simple labeling of microfossil assemblages containing "Cretaceous nannofossil taxa" and "Tertiary foraminifera taxa" as "reworked" has prevented recognition of actual transition sequences.

Above the Cretaceous-Tertiary boundary, the lower Paleocene, subdivided by planktonic foraminifera into several zones (and subzones), corresponds to the *Cruciplacolithus tenuis* Zone (nannoplankton). The boundary between the Lower and Upper Paleocene is identically drawn on the basis of nannofossils and planktonic foraminifera.

Paleocene-Eocene Boundary

Paleocene-Eocene boundary assemblages were recovered in Hole 47.2, Core 8. There are no radiolarians in this core, but an abundance of both nannoplankton and foraminifera allows a comparison of those groups. A close correlation exists between the boundaries of the zones defined by nannoplankton and foraminifera. Bramlette and Sullivan (1961) provisionally considered the *Discoaster multiradiatus* Zone of nannoplankton to be uppermost Paleocene (super-Thanetian or Sparnacian). They considered the zone to be a probable marine equivalent of the Sparnacian. According to the DSDP recommended time-stratigraphic framework (Peterson *et al.,* 1970), only the Thanetian constitutes the upper Paleocene, and only the Ypresian constitutes the lower Eocene. As the general opinion of the participants of the Eocene Colloquium at Paris in 1968 was to consider the *D. multiradiatus* Zone pivotal, with the Paleocene-Eocene boundary drawn variously within or above this limited zone, the lack of a convenient type-stage concept seems to be the only limitation to assigning this zone to the Upper Paleocene. From the standpoint of the nannoplankton assemblage, the greatest change occurs toward the top of the zone, where species such as *Discoaster multiradiatus, D. lenticularis, Ellipsolithus distichus, Rhomboaster cuspis, Sphenolithus anarrhopus* and *Toweius craticulus* become rare or absent. Several distinctive new species first appear in the *Discoaster diastypus* Zone directly above.

From the standpoint of foraminifera, the *D. multiradiatus* Zone is equivalent to the *Globorotalia subbotinae* Zone of foraminifera, but the appearance of a number of species of *Globorotalia, Globigerina, Acarinina* and *Pseudohastigerina* which persist into the younger sediment of the Lower Eocene has tempted many to draw the Paleocene-Eocene boundary at the base of the *Globorotalia subbotinae* Zone. Some micropaleontologists would place this boundary a little higher, such that the Illerdian Stage of the Paleocene includes a part of the *G. subbotinae* Zone. At Site 47, the differing selection of the Paleocene-Eocene boundary at the top or bottom of the *G. subbotinae* Zone = *D. multiradiatus* would represent a 3-meter offset, but the low sedimentation rates for this part of the section (2 to 4 meters per million years) would yield approximately a million-year time difference. Considering the problems of the present system of correlating worldwide boundaries by several microfossil groups from inadequate type sections to diverse sedimentary sections, the million-year difference is largely a function of different definitions.

Eocene-Oligocene Boundary

The stratigraphic interval near the Eocene-Oligocene boundary was cored only once (Site 44) and the lowest nannoplankton zone of the Oligocene (*Helicopontosphaera reticulata* Zone) was not encountered. This zone might have been represented in a partial core loss. No boundary sequence is available for purposes of comparison.

Oligocene-Miocene Boundary

Determination of a boundary demarcating Upper Oligocene and Lower Miocene sediment is complicated by the continuity of oceanic sedimentation and by slight evolution in microfossils during this portion of the geologic record. Richly fossiliferous Upper Oligocene and Lower Miocene sediment was sampled at Sites 55, 56 and 58 in the Caroline Ridge area. As a rule, zones (foraminifera–nannoplankton–radiolarians) are correlated as follows: *Globigerina ciperoensis–Sphenolithus ciperoensis–Lychnocanium bipes; Globorotalia kugleri*–lower *Triquetrorhabdulus carinatus*–lower *Calocycletta virginis; Globigerinita dissimilis*–upper *T. carinatus*–upper *C. virginis.* At Site 55, however, the *L. bipes* Zone corresponds also to the *G. kugleri* Zone–lower *T. carinatus* Zone.

The Oligocene-Miocene boundary is generally chosen at the top or bottom of the *G. kugleri* Zone of foraminifera. The stratigraphic level of the base of the *G. kugleri* Zone corresponds to a distinct change in assemblages of planktonic foraminifera between the *G. ciperoensis* and *G. kugleri* Zones. However, for nannoplankton and radiolarians the change in assemblages at the top of the lower *T. carinatus* Zone and *L. bipes* Zone (approximating the top of the *G. kugleri* Zone) are as distinctive as those at the bottom. Therefore, determination of an Oligocene-Miocene boundary in deep-ocean sediment is largely presumptive. The basic difficulty involved in the selection of a universal boundary between the Oligocene and Miocene is the lack of planktonic assemblages in the appropriate type stages of Europe. The Deep Sea Drilling Project biostratigraphy panel recommended the Chattian and Bormidian Stages as standard for the upper Oligocene, and the Girondian and Aquitanian Stages for the Lower Miocene (Peterson *et al.,* 1970). Nannoplankton and radiolarian workers have few, if any, direct references to these stages and must rely on indirect reference sections. Nannoplankton assemblages indirectly correlated to this interval show only minor changes in species composition. Thus Bramlette and Wilcoxon (1967), in a study of nannoplankton from the classic microfossiliferous Cipero Formation of Trinidad, established the *Triquetrorhabdulus carinatus* Zone, which includes part of both Upper Oligocene and Lower Miocene. In study of DSDP cores from Leg 3 in the South Atlantic Ocean (Bukry and Bramlette, 1970) and from Leg 4 in the Caribbean Sea (W. W. Hay, personal communication), it was noted that species such as *Discoaster druggii* and *Orthorhabdus serratus* are restricted to the upper part of the *T. carinatus* Zone. Cores from Leg 6 reveal this same relationship with the added criterion that common *Coccolithus* sp. aff. *C. bisectus* does not range above the middle of the *T. carinatus* Zone. Therefore two local subzones are recognized, a lower *Coccolithus* sp. aff. *C. bisectus* Subzone and an upper *Discoaster druggii* Subzone. The boundary between the subzones closely approximates that of the top of the *G. kugleri* Zone of foraminifera. The arbitrary Oligocene-Miocene boundary of radiolarians, the top of the *L. bipes* Zone and the base of the *C. virginis* Zone, likewise coincides with the tops of the nannoplankton *C.* sp. aff. *C. bisectus* Subzone and the foraminiferal *G. kugleri* Zone at Site 55. The exact interrelations of zone boundaries is still uncertain, however, because of the broad sampling interval in this study and possible disturbances due to the drilling process.

Though there are good arguments for selection of either the bottom or top of the *G. kugleri* Zone interval as an Oligocene-Miocene boundary in deep-sea sediment, the top of this zone was arbitrarily used for calculation of sedimentation rates and for general discussion purposes.

As regards boundaries within the Miocene, the lower-middle Miocene boundary on the basis of planktonic foraminifera and radiolarians is in close agreement (the top of the *Globigerinatella insueta* Zone—the top of the *Calocycletta costata* Zone). Concordant results were obtained from examination of nannoplankton (the top of the *Helicopontosphaera ampliaperta* Zone). The boundary between the *H. ampliaperta* and *Sphenolithus heteromorphus* Zones was drawn only conditionally because of the transitional character of the nannoplankton.

The boundary between the Middle and Upper Miocene is drawn variously owing to different understandings of the stratigraphic position of the Tortonian Stage (upper part of the Middle Miocene or lower part of the Upper Miocene).

Basal layers of the *Globorotalia menardii* Zone in the Tortonian Stage of planktonic foraminifera correspond to the *D. hamatus* and *C. coalitus* nannoplankton Zones, which are placed (on the basis of nannoplankton) at the top or above the Langhian Stage. Though these zones have been dealt with as Middle Miocene (Bramlette and Wilcoxon, 1967, pp. 108 and 110), their association with Tortonian foraminifera suggests that they be considered Upper Miocene when the Tortonian is assigned to the Upper Miocene (Peterson and others, 1970).

The boundary between the Tortonian and Messinian Stages of the upper Miocene on the basis of nannofossils is drawn 3 meters above the contact of these stages as determined by planktonic foraminifera.

The upper part of the *Globorotalia miocenica* Zone (Messinian Stage as determined by foraminifera) corresponds to the *C. rugosus* Zone, which is considered (on the basis of nannoplankton) as the transition from the Upper Miocene to the Lower Pliocene.

Miocene-Pliocene Boundary

Determination of the Miocene-Pliocene boundary by nannoplankton is not as clear as is the distinction at the top of the Pliocene. The nannoplankton zonal units involved are the Upper Miocene *Ceratolithus tricorniculatus* Zone and the Upper Miocene or Lower Pliocene *Ceratolithus rugosus* Zone. Although the disappearance of *Discoaster quinqueramus* and *Triquetrorhabdulus rugosus,* the initial appearance of *Ceratolithus rugosus,* and certain changes in the form of *Ceratolithus tricorniculatus* (Bukry and Bramlette, 1968) can be broadly applied as distinctions between Upper Miocene and Lower Pliocene nannoplankton assemblages, there remains the question of the precise correlation of such changes to the type and neotype stages in Italy. Nannoplankton assemblages there are somewhat sporadic and impoverished. In Leg 6 cores, a consistent correlation between the *Ceratolithus tricorniculatus* Zone of nannoplankton and the lower *Globorotalia miocenica*

Zone of foraminifera exists for the upper Miocene (Messinian). There is a further correlation in Hole 47.2, Core 5, between the Upper Miocene *G. tumida tumida–S. paenedehiscens* Subzone of the *G. miocenica* Zone and the *Ceratolithus rugosus* Zone. As fully representative radiolarian assemblages are not available and the upper *Ceratolithus rugosus* Zone was not cored, a complete comparison of the three microfossil groups at this boundary is not possible.

Miocene and Lower Pliocene Radiolaria zones have not been proposed for the North Pacific. The first appearance of *Stichocorys peregrina,* which defines the bottom of the Upper Miocene *Stichocorys peregrina* Zone in equatorial regions, occurs in Hole 47.2 near the top of Core 7 which agrees with the late Miocene age for Core 6 based on calcareous microfossils.

Pliocene-Pleistocene Boundary

The Pliocene-Pleistocene boundary determined by nannofossils, planktonic foraminifera and radiolarians is practically the same (bottom of the *Globorotalia truncatulinoides–Coccolithus doronicoides–Eucyrtidium matuyamai* Zones). This is true both for the tropical area (the Caroline Ridge, Hole 55.0, data on planktonic foraminifera and nannoplankton give exact coincidence) and for the more northern region (in Hole 47.2) on the Shatsky Rise; the Pliocene-Pleistocene boundary based on planktonic foraminifera is drawn 0.5 meter above this boundary determined by nannoplankton and 1.5 meters below it determined by radiolarians.

For nannoplankton, the Pliocene-Pleistocene boundary is determined as the boundary between the upper Pliocene *Discoaster brouweri* Zone and the lower Pleistocene *Coccolithus doronicoides* Zone. Several significant changes in coccolith assemblages occur near this boundary. The typical Pliocene species *Ceratolithus rugosus, Cyclococcolithus macintyrei* and *Discoaster brouweri* are abruptly reduced in abundance. This change is observed to co-occur with the transition from *Globorotalia tosaensis* to *G. truncatulinoides* among the foraminifera in Hole 47.2, Core 2, and Hole 55.0, Core 1. In Hole 47.2, Core 2, where radiolarians are also present, the boundary between the Upper Pliocene *Lamprocyclas heteroporos* Zone and Lower Pleistocene *E. matuyamai* Zone is observed to occur some 2 meters above the Pliocene-Pleistocene boundary of calcareous microfossils. If a similar relationship is confirmed in future drilling, a combination zone based on the changes in nannoplankton and foraminifera at the bottom and on radiolarians at the top may help to refine the division of the Lower Pleistocene.

Zonal Summary

A comparison of zone and series boundaries determined by the three major microfossil groups in the cores of Leg 6 suggests that present zonal boundaries are too similar for the overlaps to be consistently used in themselves as criteria for new subzonal divisions combining two or more groups. The fairly close agreement of the limits of zones between the microfossil groups may be in part circular, as nannoplankton zones have commonly been established in strata previously zoned by the use of planktonic foraminifera. Further, the radiolarian zonation was in large measure developed from studies of deep-ocean cores, which also have been correlated by planktonic foraminifera or nannoplankton. All three groups of microfossils are the products of planktonic unicellular organisms that have undergone concurrent stress in the same physical environment, probably resulting in significant morphologic changes at roughly similar times. Nevertheless, intergroup differences in zone-boundary levels in the cores may be quite significant in areas of low sedimentation rate. With a sedimentation rate of a few Bubnoff units, a stratigraphic difference of meter magnitude represents an age difference of million-year magnitude—the general duration of biostratigraphic-zone intervals.

Ideally, a comparison of the species ranges of nannoplankton, planktonic foraminifera, and radiolarians in richly fossiliferous continuously cored sections from various latitudes could well define a highly precise specialized zonation. The key to development of such a system could lie in more detailed studies of the Deep Sea Drilling Project cores. Sampling intervals employed for the initial reports on these cores is commonly only 75 or 150 centimeters, such that boundaries and ranges could be more precisely delineated by future work on the intervals where major changes are indicated.

PALEOECOLOGY

Calcareous Nannoplankton

Our present understanding of the ecology and paleoecology of calcareous nannoplankton is limited. But the present and fossil occurrences clearly indicate that significant assemblages are preserved as skeletal hardparts only in sediment deposited under fully marine to slightly brackish conditions. Some distinctions can be made, however, between nannoplankton assemblages from open-ocean areas and from shelf or nearshore areas. Moreover, warm and cool water assemblages can be broadly distinguished by such characters as the discoaster species present.

Even the most northern Leg 6 drilling localities (Shatsky Rise, Sites 47 to 50, latitude 32° North) are presently under the sway of the warm Japan Current, and late Cenezoic nannoplankton assemblages here are only slightly different from the tropical assemblages of the southern drilling localities (Caroline Ridge, Sites 55 to 58, 9° north latitude). For example, the southern localities lack *Discoaster exilis,* but have abundant

Sphenolithus abies and common *Scyphosphaera* sp. cf. *S. apsteinii* in Upper Miocene and Pliocene assemblages. The northern localities lack *S.* sp. cf. *S. apsteinii,* and have rare *S. abies* and frequent *D. exilis.* Common occurrence of *D. exilis* in Upper Pliocene assemblages with cool-water affinities is also indicated by the abundance of this species with respect to *Discoaster brouweri* in northeastern Pacific and Italian Upper Pliocene sediment.

Certain nannoplankton genera that are common to abundant in Eocene nannoplankton assemblages from shelf or nearshore deposits are conspicuously absent in cores from the open-ocean environment. For example, a comparison of Leg 6 Cenozoic assemblages with those of California, Gulf Coast and Blake Plateau sections shows that open-ocean assemblages are less diversified and lack species of such genera as: *Braarudosphaera, Clathrolithus, Daktylethra, Lanternithus, Micrantholithus, Orthozygus, Pemma, Peritrachelina, Rhabdosphaera, Transversopontis* and *Zygrhablithus.* The characteristic nearshore species *Zygolithus dubius* is also missing. Sullivan (1965) suggested that the presence of *Braarudosphaera* indicated a shallow-water environment. Bramlette and Martini (1964), however, considered that genus to be indicative of nearshore conditions, the actual depth of the water being a subsidiary factor. The exclusion of *Rhabdosphaera* from open-ocean sediment of the Eocene was pointed out by M. N. Bramlette (personal communication, 1967), with the additional paleoecologic information that *Rhabdosphaera* is present in open-ocean upper Cenozoic sediment. This distribution is supported by evidence from Leg 6 cores and implies a change in the ecologic tolerance of *Rhabdosphaera* during the Cenozoic. For other genera, such as *Clathrolithus, Daktylethra, Lanternithus, Orthozygus, Peritrachelina,* and *Zygrhablithus,* Gartner and Bukry (1969) suggested preferential preservation in rapidly accumulated clay-rich marl in shelf and nearshore areas rather than open-ocean areas contributed to their abundance. Thus, the physical-chemical factors associated with sediment type and water depth at deposition may influence the preservability of certain taxa and make ecologic interpretations more complicated.

Although precise ecologic controls cannot yet be marshalled to explain all observed occurrences, the taxonomic distinctness of open-ocean assemblages is generally apparent (Table 1).

TABLE 1
Comparison of Lower Tertiary Calcareous Nannoplankton Assemblages in Oceanic and Nearshore Areas. Asterisk means the Taxon is not Identified in Open-Ocean Sediment of the Northwestern Pacific and May Prove Useful for Distinguishing Shallow or Nearshore Basin and Shelf Paleogeography

OPEN OCEAN	NEARSHORE BASIN AND SHELF
LOWER OLIGOCENE NORTHWESTERN PACIFIC OCEAN, LEG 6 HORIZON RIDGE, HOLE 44, CORE 1	LOWER OLIGOCENE VICKSBURG GROUP AND RED BLUFF CLAY GULF COASTAL PLAIN, U.S.A.; AND BLAKE PLATEAU JOIDES CORES, WESTERN ATLANTIC OCEAN
Bramletteius serraculoides	*_Braarudosphaera bigelowi_
Coccolithus bisectus	*_B. rosa_
C. eopelagicus	_Bramletteius serraculoides_
C. pelagicus	_Coccolithus bisectus_
_C._ sp. cf. _C. scissurus_	_C. eopelagicus_
Cyclococcolithina formosus	_C. pelagicus_
C. neogammation	_C._ sp. cf. _C. scissurus_
Discoaster deflandrei	*_C. subdistichus_
D. tani tani	_Cyclococcolithina formosus_
Helicopontosphaera reticulata?	_C. neogammation_
Leptodiscus larvalis	_Discoaster deflandrei_
Pontosphaera vadosa	_D. tani nodifer_
Reticulofenestra umbilica	_D. tani tani_
Sphenolithus distentus	*_Discolithina_ sp. cf. _D. distincta_
S. moriformis	*_D. macropora_
S. predistentus	_D. plana_
S. pseudoradians	_Helicopontosphaera compacta_

TABLE 1 – *Continued*

OPEN OCEAN	NEARSHORE BASIN AND SHELF
	LOWER OLIGOCENE – *Continued*
	H. intermedia
	H. parallela
	H. reticulata
	Isthmolithus recurvus
	*_Lanternithus minutus_
	Leptodiscus larvalis
	*_Micrantholithus_ sp. aff. _M. attenuatus_
	*_Orthozygus aureus_
	*_Peritrachelina joidesa_
	*_Quinquerhabdus colossicus_
	Reticulofenestra gartneri
	R. umbilica
	*_Rhabdosphaera spinula_
	*_R. tenuis_
	*_R. vitrea_
	Sphenolithus moriformis
	S. predistentus
	S. pseudoradians
	*_Transversopontis pulcher_
	*_T. zigzag_
	*_Zygrhablithus bijugatus_
UPPER EOCENE NORTHWESTERN PACIFIC OCEAN, LEG 6 HORIZON RIDGE, HOLE 44, CORE 2	UPPER EOCENE JACKSON GROUP, GULF COASTAL PLAIN, U.S.A.; AND BLAKE PLATEAU JOIDES CORES, WESTERN ATLANTIC OCEAN
Bramletteius serraculoides	
Chiasmolithus oamaruensis	*_Braarudosphaera bigelowi_
Coccolithus bisectus	*_B. discula_
C. eopelagicus	_Bramletteius serraculoides_
C. pelagicus	_Chiasmolithus oamaruensis_
Cyclococcolithina formosus	_Coccolithus bisectus_
Discoaster barbadiensis	_C. eopelagicus_
D. deflandrei	_C. pelagicus_
D. saipanensis	_C._ sp. cf. _C. scissurus_
D. tani nodifer	_Cyclococcolithina formosus_
D. tani tani	_C. neogammation_
Isthmolithus recurvus?	*_C. reticulatus_
Leptodiscus larvalis	_Discoaster barbadiensis_
Pontosphaera vadosa	_D. deflandrei_
Reticulofenestra umbilica	_D. saipanensis_
Sphenolithus sp. aff. _S. moriformis_	_D. tani nodifer_
S. pseudoradians	_D. tani tani_
	*_Discolithina_ sp. cf. _D. distincta_
	*_D. macropora_
	D. plana
	*_Hayella situliformis_
	Helicopontosphaera compacta
	H. intermedia
	H. reticulata
	Isthmolithus recurvus
	*_Lanternithus minutus_

TABLE 1 – *Continued*

OPEN OCEAN	NEARSHORE BASIN AND SHELF
	UPPER EOCENE – *Continued*
	**Leptodiscus larvalis*
	**Lithostromation perdurum*
	**Micrantholithus* sp. aff. *M. attenuatus*
	**M. basquensis*
	**Orthozygus aureus*
	**Pemma papillatum*
	**Peritrachelina joidesa*
	Reticulofenestra umbilica
	**Rhabdosphaera spinula*
	**R. tenuis*
	**R. vitrea*
	Sphenolithus moriformis
	S. predistentus
	**Transversopontis pulcher*
	**T. zigzag*
	**Zygrhablithus bijugatus*
MIDDLE EOCENE NORTHWESTERN PACIFIC OCEAN, LEG 6 HORIZON RIDGE, HOLE 44, CORES 3-5	MIDDLE EOCENE CLAIBORNE GROUP, GULF COASTAL PLAIN, U.S.A.; AND BLAKE PLATEAU JOIDES CORES, WESTERN ATLANTIC OCEAN
Bramletteius serraculoides	
Campylosphaera dela	**Braarudosphaera bigelowi*
Chiasmolithus expansus	**B. discula*
C. grandis	*Bramletteius serraculoides*
C. solitus	*Campylosphaera dela*
Coccolithus bisectus	*Chiasmolithus expansus*
C. eopelagicus	*C. gigas*
C. pelagicus	*C. grandis*
Cyclococcolithina formosus	*C. solitus*
Discoaster barbadiensis	*C. staurion*
D. tani nodifer	*Coccolithus bisectus*
Helicopontosphaera compacta	*C. eopelagicus*
H. reticulata?	*C. pelagicus*
Leptodiscus larvalis	*Cyclococcolithina formosus*
Pontosphaera vadosa	*C. gammation*
Reticulofenestra dictyoda	*C. luminis*
R. umbilica	**Daktylethra punctulata*
Sphenolithus sp. aff. *S. moriformis*	*Discoaster barbadiensis*
S. pseudoradians	*D. distinctus*
S. radians	*D. elegans*
Thoracosphaera prolata	*D. saipanensis*
Triquetrorhabdulus inversus	*D. stradneri*
	D. tani nodifer
	**Discolithina distincta*
	**D. panarium*
	**Helicopontosphaera seminulum*
	**H. lophota*
	**Lanternithus minutus*
	**Markalius inversus*
	**Micrantholithus basquensis*
	**M. crenulatus*

TABLE 1 – *Continued*

OPEN OCEAN	NEARSHORE BASIN AND SHELF
	MIDDLE EOCENE – *Continued* **M. fos.* **M. procerus* **Pemma papillatum* *Reticulofenestra dictyoda* *R. umbilica* **Rhabdosphaera crebra* **R. morion* *Sphenolithus radians* **Syracosphaera labrosa* *Thoracosphaera prolata* **Transversopontis pulcher* *Triquetrorhabdulus inversus* **Zygolithus dubius* **Zygrhablithus bijugatus*
LOWER EOCENE NORTHWESTERN PACIFIC OCEAN, LEG 6 SHATSKY RISE, HOLE 47.2, CORES 7-8 *Campylosphaera dela* *Chiasmolithus bidens* *C. consuetus* *C. grandis* *C. solitus* *Chiphragmalithus calathus* *Coccolithus crassus* *C. cribellum* *C. pelagicus* *Cyclococcolithina formosus* *C. gammation* *Discoaster barbadiensis* *D. diastypus* *D. keupperi* *D. lodoensis* *D. mirus* *D. robustus* *D. wemmelensis* *Discolithina rimosa* *Lophodolithus nascens* *Lucianorhabdus dispar* *Marthasterites tribrachiatus* *Sphenolithus radians*	LOWER EOCENE UPPER PART OF LODO FORMATION, CALIFORNIA, U.S.A.; AND BLAKE JOIDES CORES, WESTERN ATLANTIC OCEAN **Braarudosphaera bigelowi* **B. discula* *Campylosphaera dela* *Chiasmolithus consuetus* *C. grandis* **Clathrolithus ellipticus* *Coccolithus crassus* *C. cribellum* *C. pelagicus* *Cyclococcolithina formosus* *C. gammation* *Discoaster barbadiensis* *D. diastypus* *D. distinctus* *D. elegans* *D. germanicus* *D. kuepperi* *D. lodoensis* *D. septemradiatus* **Discolithina ocellata* **D. pectinata* *D. plana* *D. rimosa* *D. versa* **Helicopontosphaera seminulum* *Lophodolithus nascens* *Marthasterites tribrachiatus* **Micrantholithus attenuatus* **M. flos* **M. vesper* **Rhabdosphaera crebra*

TABLE 1 – _Continued_

OPEN OCEAN	NEARSHORE BASIN AND SHELF
	LOWER EOCENE – _Continued_
	*_R. perlonga_
	*_R. scabrosa_
	*_R. truncata_
	Sphenolithus radians
	*_Transversopontis pulcher_
	*_Zygolithus dubius_
	*_Zygrhablithus bijugatus_
UPPER PALEOCENE NORTHWESTERN PACIFIC OCEAN, LEG 6 SHATSKY RISE, HOLE 47.2, CORES 8-9 ABYSSAL BASIN, HOLE 59.2, CORE 6	UPPER PALEOCENE LOWER PART OF LODO FORMATION, CALIFORNIA, U.S.A.; AND BLAKE JOIDES CORES, WESTERN ATLANTIC OCEAN
Campylosphaera dela	*_Braarudosphaera bigelowi_
Chiasmolithus bidens	*_B. discula_
C. californicus	_Campylosphaera dela_
C. consuetus	_Chiasmolithus bidens_
Coccolithus pelagicus	_C. californicus_
Cruciplacolithus tenuis	_C. consuetus_
Cyclolithella? robusta	*_Clathrolithus ellipticus_
Discoaster sp. aff. _D. gemmeus_	_Coccolithus cribellum_
D. helianthus	_C. pelagicus_
D. lenticularis	_Cyclolithella? robusta_
D. multiradiatus	_Discoaster falcatus_
D. ornatus	_D._ sp. aff. _D. gemmeus_
Discolithina rimosa	_D. helianthus_
Ellipsolithus distichus	_D. limbatus_
E. macellus	_D. mediosus_
Fasciculithus involutus	_D. multiradiatus_
F. tympaniformis	_Discolithina plana_
Heliolithus kleinpelli	_D. rimosa_
H. riedeli	*_D. solida_
Rhomboaster cuspis	_Ellipsolithus distichus_
Sphenolithus anarrhopus	_E. macellus_
Toweius craticulus	_Fasciculithus involutus_
T. eminens	*_F._ sp. cf. _F. schaubi_
Zygodiscus sigmoides	_F. tympaniformis_
Zygrhablithus simplex	_Heliolithus kleinpelli_
	H. riedeli
	Heliorthus concinnus
	*_Micrantholithus bramlettei_
	*_M. entaster_
	*_M. pinguis_
	Rhomboaster cuspis
	Scapholithus apertus
	Sphenolithus anarrhopus
	Toweius craticulus
	T. eminens
	Zygodiscus plectopons
	Z. sigmoides
	Zygolithus chiastus
	Zygrhablithus simplex

The absence of the Tithonian (Late Jurassic) and Neocomian (Early Cretaceous) nannoplankton genus *Nannoconus* and the protozoan *Calpionella* in sediment from the Shatsky Rise may be attributed to paleoecologic or preservational factors. Pelagic deep-water sediment of similar age from the ancient Tethys seaway of the Mediterranean region is characterized by abundant occurrences of these genera. Similar material from near the Bahama Islands (Leg 1, Sites 4 and 5) contains common *Nannoconus* but no *Calpionella.* The absence of these forms in pelagic sediment from the Shatsky Rise might be considered a result of solution, but the assemblage of other nannoplankton genera is so similar in abundance and preservation to that of the Mediterranean region and Bahama Islands that any dissolving would have to be strangely selective. An alternate explanation for this difference in distribution is that the Shatsky Rise sediment, while representing a pelagic facies, is not a typical Tethyan seaway deposit, but instead represents deposition in a different geographic setting. *Calpionella* is reported from Tethyan rock units representing deep-basin facies that grade through short distances into shallow facies (Garrison and Fischer, 1969); perhaps it is absent in normal oceanic sediment such as the Shatsky Rise deposits.

The Tethyan environment is considered to have been tropical (Sylvester-Bradley, 1968). Evidence from magnetic pole positions of Cretaceous seamounts near the Shatsky Rise suggests that the Rise had an equatorial position during the Cretaceous (Vaquier and Uyeda, 1967). Greatly different pole positions for other undated seamounts on the rise might be explained if they are Jurassic rather than Cretaceous.

In any event, a more definitive understanding of paleoecologic conditions at the Shatsky Rise will depend on future evidence. Such evidence could be obtained if the *Glomar Challenger* with new re-entry drilling capability returns to this significant area.

Radiolaria

Cenozoic radiolarian assemblages from Shatsky Rise sites lack most of the short-ranging equatorial species now used for stratigraphic zonation in low latitudes. Subarctic, central and equatorial species are intermixed in these samples (Nigrini, in press). A zonation established for high-latitude (subarctic) Pacific radiolarians (Hays, in press) is applicable to these samples, but even some of the subarctic species are rare in this area. Ideally, the stratigraphic sequences underlying all present-day water masses (equatorial, central and subarctic) should be established in order to properly date samples from a region such as the Shatsky Rise, where currents bring together species from various source regions.

Radiolarian assemblages from Sites 53 and 54 in the Philippine Basin are similar in species composition to those of similar age in other equatorial regions (Riedel, 1957; 1959). Zonations previously proposed for low latitude faunas (Riedel and Sanfilippo, in press) in deep-sea sediment and outcrops on land are applicable to the samples in this region.

At the Caroline Ridge, Cenozoic radiolarian faunas are, as those of the Philippine Basin, like those of other equatorial regions. Previously known short-ranging species are found, and zonation on the basis of radiolarians presents no problems involving biogeographic provinces.

Abyssal Pacific radiolarian assemblages deposited at great depth are affected by biogeography in the same way as those in shallower water. Thus the high-latitude sites (45, 46, 51, 52) produce, where conditions of preservation are favorable, assemblages quite different from those of the same age from the low-latitude abyssal Site 59.

PRESERVATION

Calcareous Nannoplankton

The average preservation of calcareous nannoplankton encountered in sediment of the northwestern Pacific is good. General variation owing to the diverse depths of sedimentation and sediment source at different sites (Table 2 and Plates 1 to 4) has a more obvious effect on preservation than does the age of nannoplankton-bearing sediment. For instance, Lower Cretaceous or Upper Jurassic nannoplankton are well-preserved in cores from the Shatsky Rise, whereas mid-Tertiary specimens in abyssal clay or partially indurated ooze are poorly preserved–being, respectively, partially dissolved or thickly overgrown. The comparison of preservation states for the various sites (Table 3) indicates that assemblages of Pliocene and Pleistocene nannoplankton are excellently preserved and essentially pristine.

Horizon Ridge (Site 44, depth 1478 meters) is presently an elevated ocean bottom feature, and since the nannoplankton assemblages in calcareous ooze of Oligocene and Eocene age are excellently preserved–*Chiasmolithus oamaruensis* specimens at the top of the Eocene (Core 4) retain their thin central crossbars–we infer that shallow depths, well above the calcite-compensation depth, have probably persisted since the Eocene. In sharp contrast is the irregular appearance of Oligocene specimens in nearby surficial clay and volcanic ash-rich sediment (Site 45, depth 5507 meters). These specimens are overgrown and irregularly etched in many instances, suggesting variable preservation since the Oligocene with derivation from a partially lithified ooze and possible resedimentation at this site. Rare Eocene specimens in volcanic-ash-rich sediment from 58 meters subbottom

TABLE 2
Qualitative State of Microfossil Preservation in Different Sediment Types From the Northwestern Pacific Ocean, Deep Sea Drilling Project, Leg 6

SEDIMENT TYPE	NANNOPLANKTON	FORAMINIFERA	RADIOLARIA
CHALK OOZE	Coccoliths–slightly overgrown; average to excellent Discoasters–heavily overgrown; average to poor	Deposits above 4000 m: good to excellent, many pristine Deposits below 4000 m: fair to good; traces of solution with increasing depth	Average to excellent
MARL OOZE	Average to excellent	Same as above	Average
SILICA OOZE	Coccoliths–slight to extensive dissolution; average to poor Discoasters–pristine? to moderate dissolution; average to excellent	(No foraminifera)	Average or better
SOFT LIMESTONE	Coccoliths–slight to heavy overgrowth; average to poor Discoasters–heavy overgrowth; poor to nonidentifiable	Fair to good; traces of solution	Poor (quartzified) to moderately well-preserved
CHERT	(None identified)	(None identified)	Generally poor, altered rarely pyritized
VOLCANIC ASH	Coccoliths–slight to extensive dissolution; average to poor Discoasters–pristine? to moderate dissolution; average to excellent	Fair to good; many broken; traces of solution	Average or better
ASH AND BROWN CLAY	Poor to average with extensive dissolution	(No foraminifera)	Average
ZEOLITIC BROWN CLAY	Poor to average with extensive dissolution	Deposits from 5000 m: very poor; extensive dissolution	Poor
BROWN CLAY	Poor to average with extensive dissolution (usually absent)	(No foraminifera)	Poor

TABLE 3
Qualitative Comparison of Preservation State of Calcareous Nannoplankton with Respect to Geologic Series, Deep Sea Drilling Project Leg 6 Northwestern Pacific Ocean
E–excellent, A–average, P–poor

SERIES / SITE	PLEISTOCENE	PLIOCENE	MIOCENE	OLIGOCENE	EOCENE	PALEOCENE	UPPER CRETACEOUS	LOWER CRETACEOUS OR UPPER JURASSIC
44				E	E			
45				P			A	
46					A			
47	E	E	E		A	E-A	A	
48		E	E				A	
49	P							A
50	E							A
51							E	
52								
53			A	P				
54			E-A					
55	E	E	A	A				
56			A-P	A				
57		E	A	E-A				
58	E	A	A	A				
59				A	A	A		
60			E-A					

are partially etched. However, the Cenomanian carbonate ooze at 86 meters subbottom is well-preserved, with no evidence of thick overgrowths or etching. This same relation between Cenozoic abyssal clay-ash sediment and Mesozoic carbonate ooze preservation was encountered at other sites in deep areas (Sites 49, 50 and 51). It has been suggested this is a typical sedimentologic situation in old areas of the ocean owing to sea-floor spreading (Fischer and Gealy, 1969). Carbonate ooze of Mesozoic age deposited in shallow depth associated with ridges (axes of sea-floor spreading) would be well-preserved; whereas in Cenozoic time, when the sea floor was at a greater distance from the ridge axes, it would also be at a deeper position with respect to sea level and the calcite-compensation level. Dissolution of calcite nannoplankton would become a significant factor if the depth of the bottom was very great (in excess of 5000 meters).

Similarly, contrasting preservation states are noted in nannoplankton from the eastern Philippine Sea. One unusual type of depositional environment represented there is thick sediment aprons of rapidly accumulated volcanic-ash at Sites 53 and 54. Nannoplankton in this sediment is generally well-preserved. The discoasters lack overgrowths, an indication of a pristine or only slightly dissolved state of preservation. A contrasting preservation state for discoasters between volcanic ash and carbonate ooze sediment has important significance for discoaster taxonomy. The precise specific characters of discoasters are commonly obscured and even distorted by post-depositional, thick, calcite overgrowths in ooze sediment (Plate 3).

At Site 53, near-surface ashy sediment has nannoplankton assemblages composed only of discoasters with their center-stems dissolved, and a surface core lacks any nannoplankton at all. An extreme case of poor preservation of nannoplankton was encountered in the soft pink limestone from the basal cores here from depths of 174 to 201 meters. Owing to thick irregular overgrowths on the specimens, only a few species of nannoplankton could be identified. This state of preservation is probably related to an early stage of cementation, the soft limestone originally having been a carbonate ooze.

As a whole, this sequence of preservational states indicates a progressively deteriorating sedimentologic environment for the preservation of calcareous nannoplankton through geologic time at Site 53. Whether this was caused by a sinking of the area related to nearby volcanism or to geochemical conditions deriving from the flood of volcanic ash is not clear for most of the cored section. But the surface core of zeolitic clay (0 to 9 meters) contains no calcareous nannoplankton or debris, suggesting the sea floor is presently below the compensation point for calcite and that the sediment has undergone diagenesis. During Oligocene or early Miocene time, however, carbonate ooze accumulated at this site.

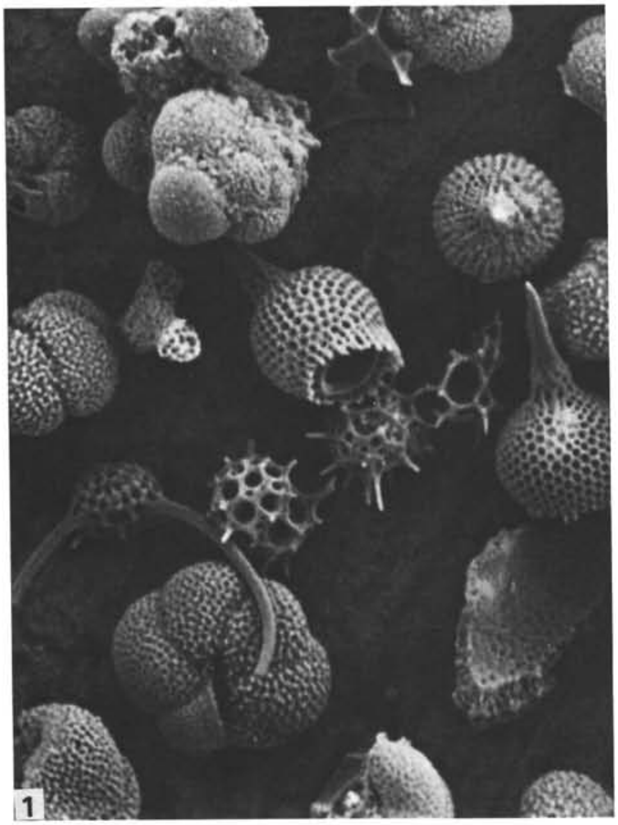
Foraminifera

Examination of the foraminifera, mainly planktonic foraminifera, from cores drilled by Leg 6 suggests that the state of preservation of these microfossils is related to two factors: (1) the accumulation of diagenetic effects with increasing age of the sediment, and (2) relation to calcite-compensation level or bathymethry at the site of deposition.

PLATE 1

Representative Preservation of Microfossils in Tropical Calcareous-Siliceous Ooze, Illustrated by Scanning Electron Microscopy of Samples from the Caroline Ridge, Site 55, Leg 6, Deep Sea Drilling Project.

Figure 1	Foraminifera and radiolarians. Sample 6-55-14, core catcher (131 m). Magnification: 130 ×.
Figure 2	Foraminifera and radiolarians. Sample 6-55-12, core catcher (113 m). Magnification: 170 ×.
Figure 3	Coccoliths and discoaster. Sample 6-55-13-5, 11-13 cm (119 m). Magnification: 8100 ×.
Figure 4	Radiolarian. Sample 6-55-10-3, 3-5 cm (85 m). Magnification: 580 ×.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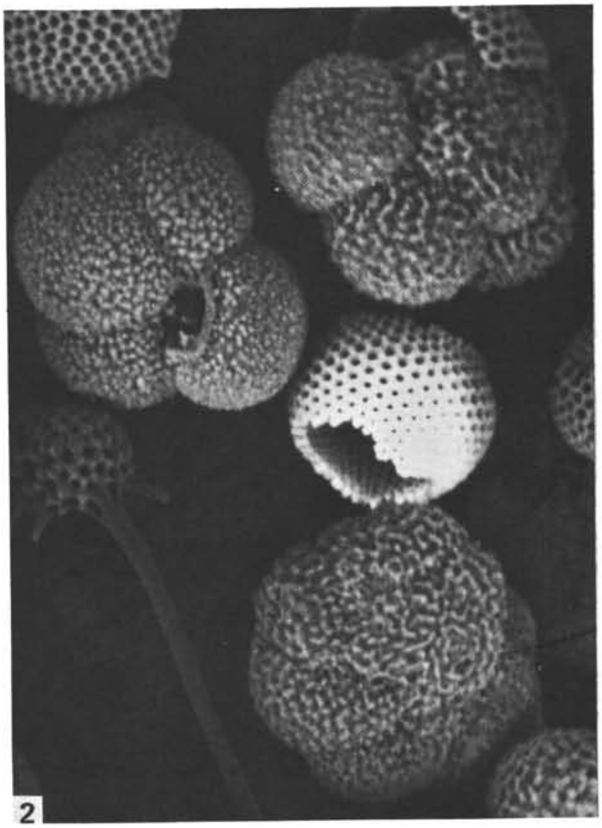
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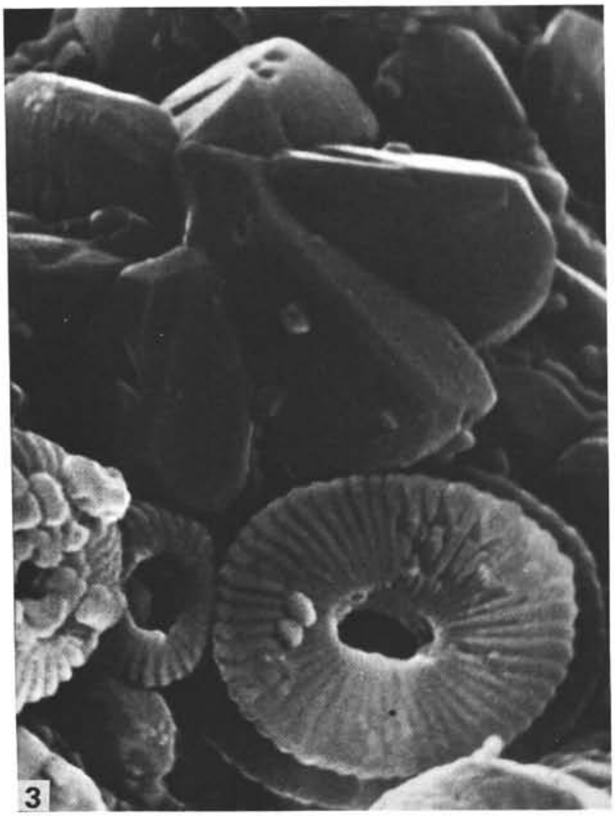
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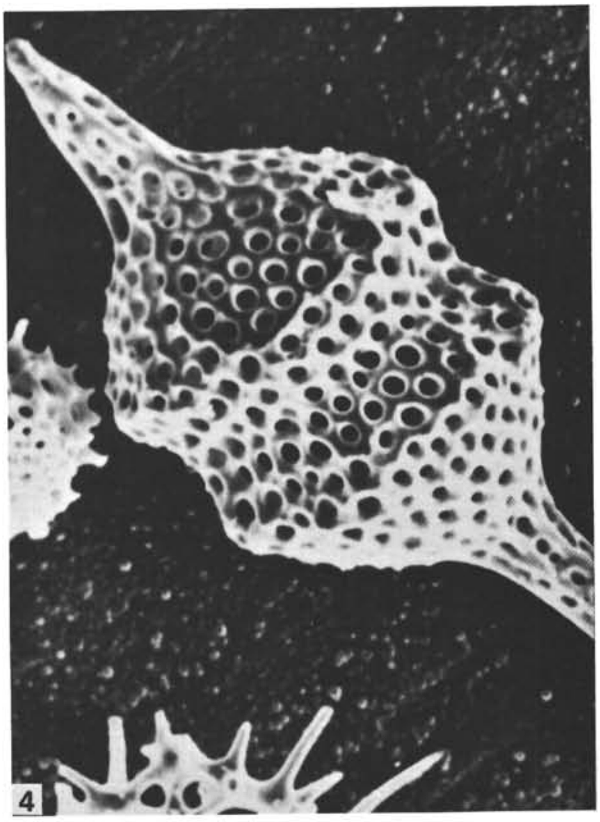
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PLATE 2

Excellent Preservation State of Radiolarian and Calcareous Nannoplanktonic Microfossils in Late Tertiary Calcareous-Siliceous Ooze of the Northwestern Pacific Ocean Illustrated by Electron Microscopy

Figure 1	Scanning electronmicrograph of early Miocene radiolarians from the Caroline Ridge. Sample 6-55-10, core catcher (91 m). Magnification: 210 ×.
Figure 2	Transmission electronmicrograph of early Pliocene calcareous nannoplankton from the Caroline Ridge. Sample 6-57.2-1-6, 0-3 cm (42 m). Magnification: 6000 ×.

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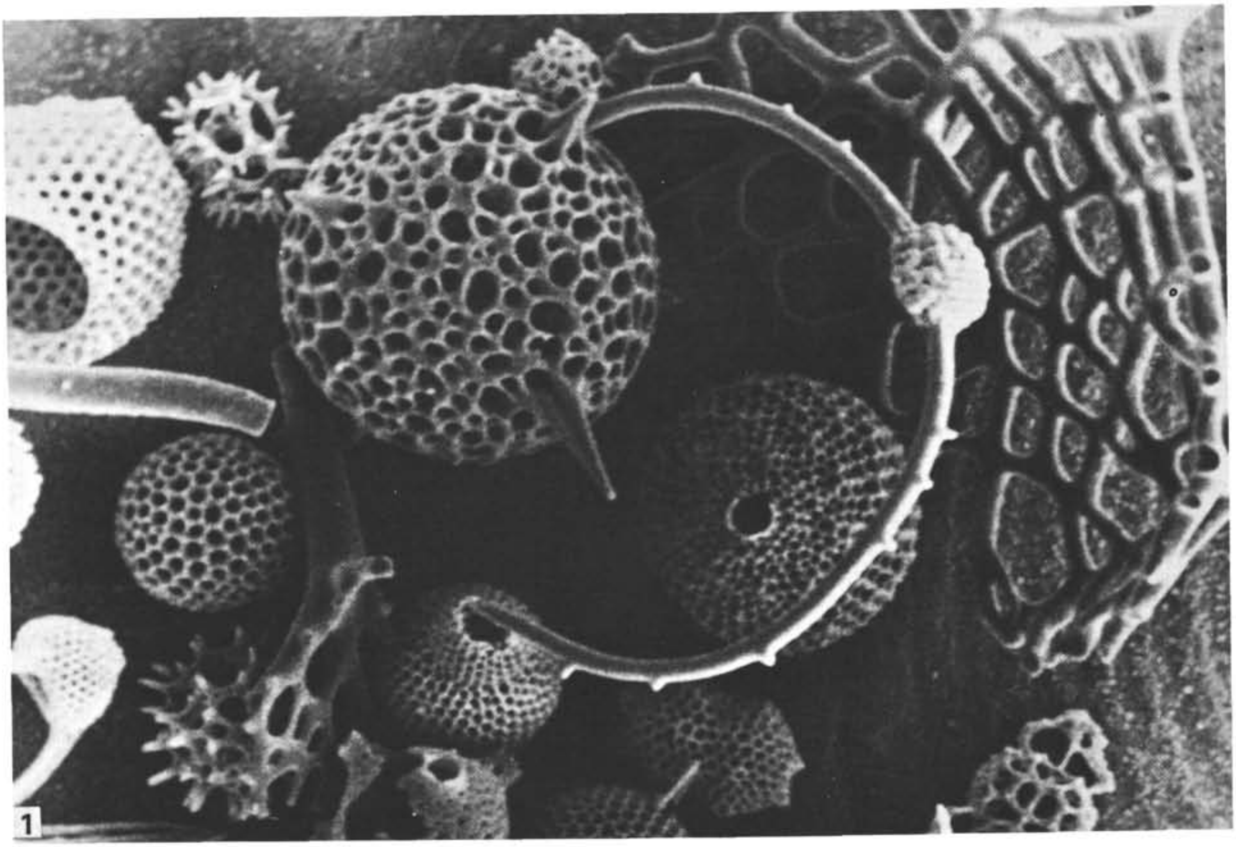

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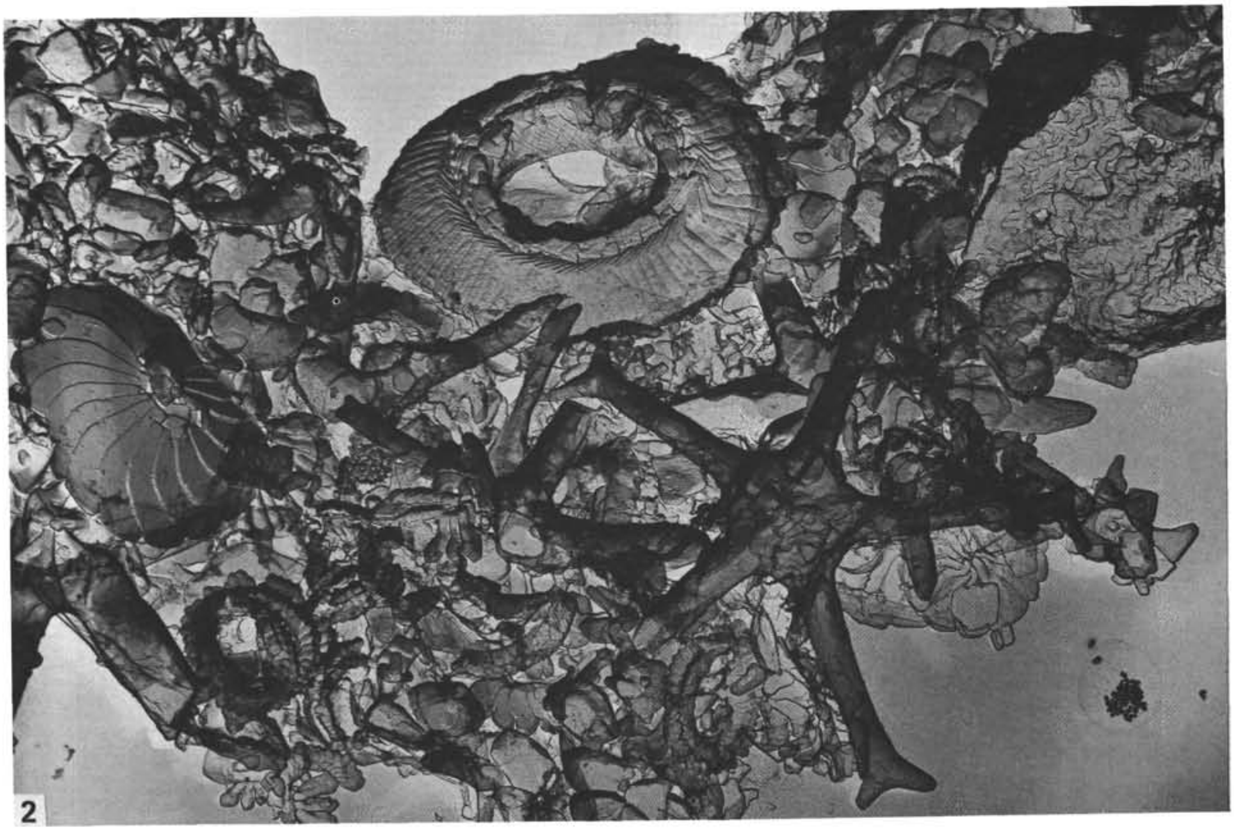
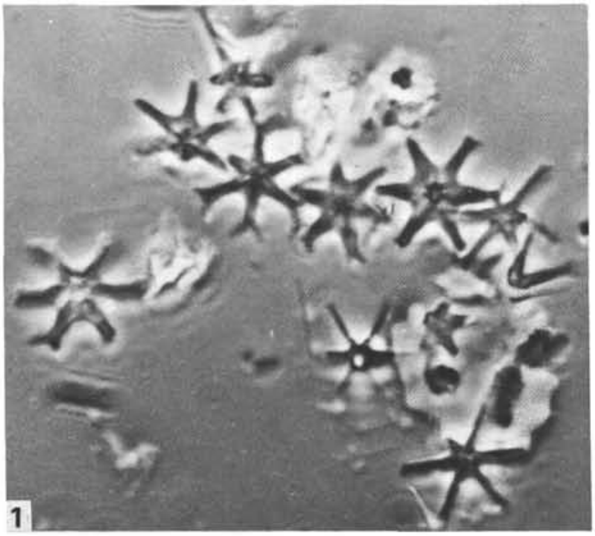


PLATE 3

Contrasting Preservation of Discoasters (Calcareous Nannoplankton) in Volcanic Ash and Calcareous Ooze Sediment of Miocene Age from the Northwestern Pacific Ocean Illustrated by Photomicrographs

Figure 1	Well-preserved discoasters from volcanic ash in the Philippine Basin. Sample 6-54.0-2-1, 126-127 cm (139 m). Magnification: 1400 X.
Figure 2	Well-preserved discoasters from calcareous ooze mixed with volcanic ash at the western margin of the Mariana Trench. Sample 6-60-1-1, 44 cm (52 m). Magnification: 610 X.
Figures 3,4&5	Specimens distorted by overgrowth of excess calcite in calcareous ooze from the Caroline Ridge. Sample 6-55-7-5, 88 cm (62 m).
Figure 6	Discoaster specimens showing thick uneven calcite overgrowths in contrast to circular coccoliths in calcareous ooze from the Caroline Ridge. Sample 6-56.2-4, core catcher (110 m). Magnification: 1000 X.



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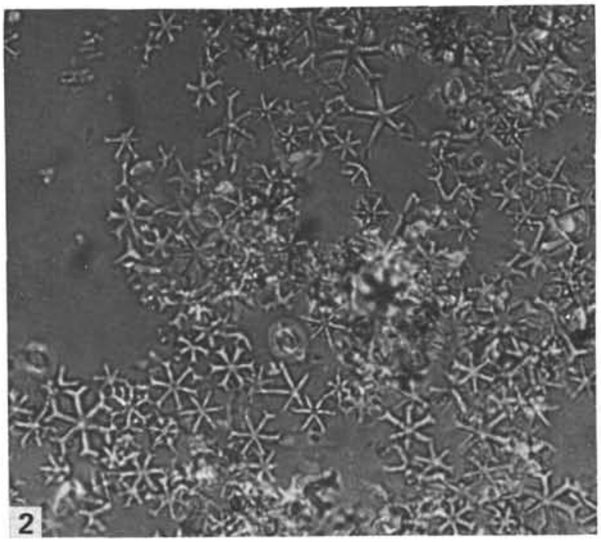

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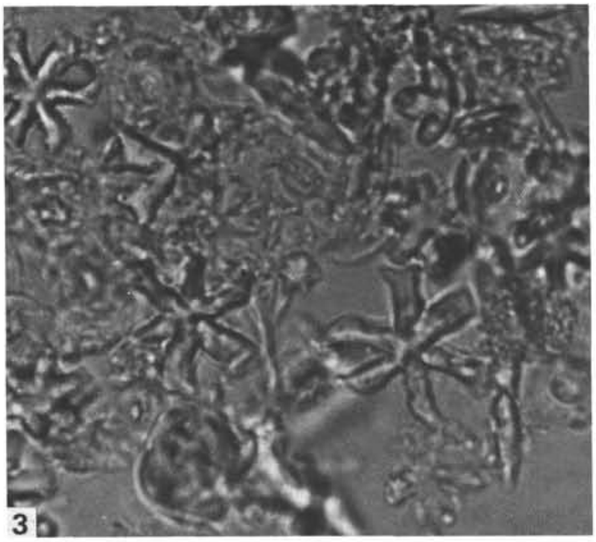

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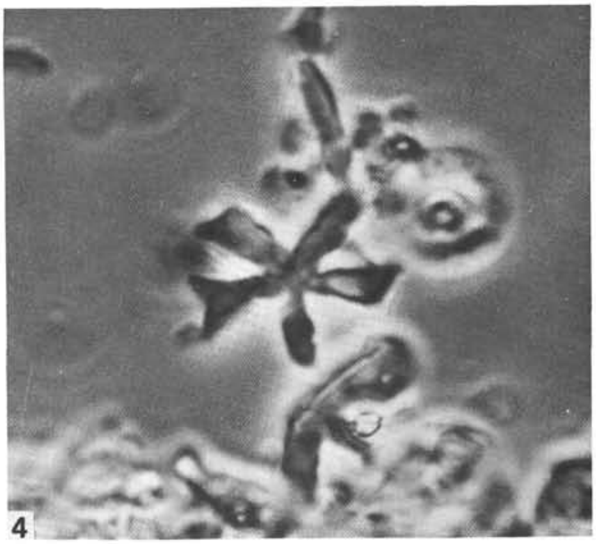

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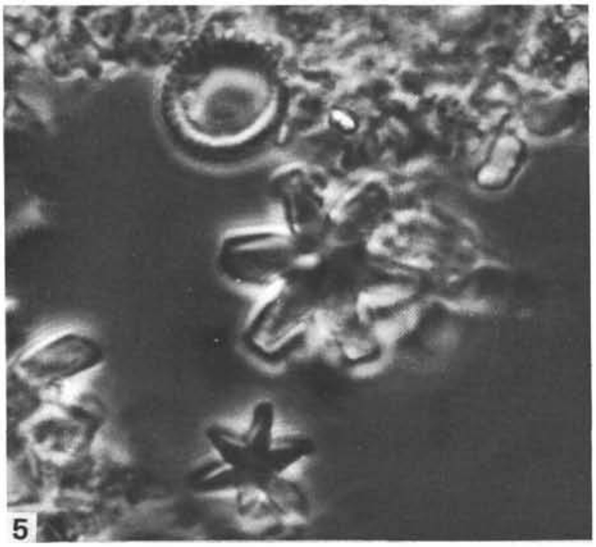

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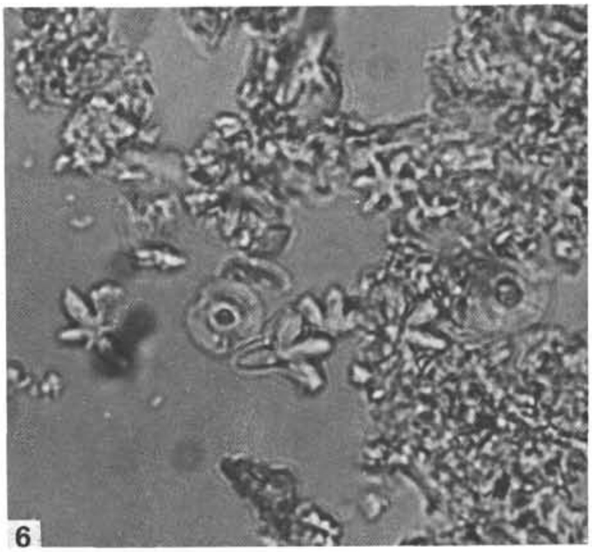

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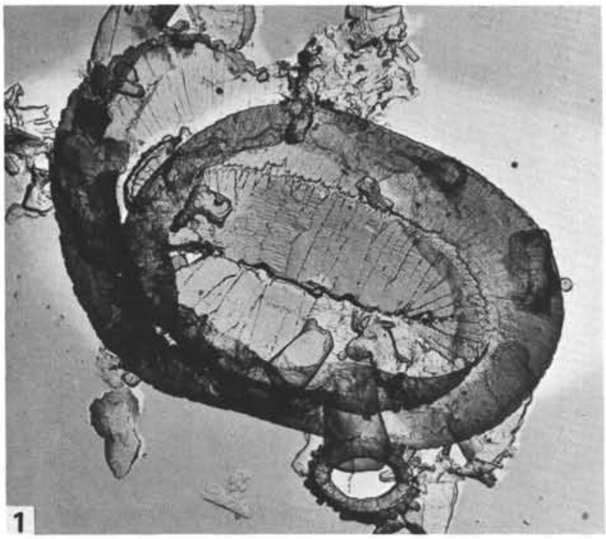
PLATE 4

Degree of Variation in Preservation of Calcareous Nannoplankton in
Oceanic Sediment is Slight When Considered Solely as a Function of Age.
Illustrations of Samples from the Northwestern Pacific Ocean are
Transmission Electronmicrographs (Figures 1-4,6) and
a Polarized Photomicrograph (Figure 5)

Figure 1	Pleistocene specimen, pristine to slightly etched. Sample 6-47.0-1-4, 77-78 cm (5 m). Magnification: 6100 X.
Figure 2	Oligocene specimen, moderately etched. Sample 6-57.0-1-1, 86-87 cm (298 m). Magnification: 7000 X.
Figure 3	Paleocene specimen, slightly overgrown. Sample 6-47.2-9-5, 77-78 cm (89 m). Magnification: 6500 X.
Figure 4	Eocene specimens, pristine to slightly overgrown. Sample 6-44-3-5, 145-150 cm (63 m). Magnification: 1600 X.
Figure 5	Tithonian or Neocomian specimens, slightly overgrown. Sample 6-50.0-1, core catcher (38 m). Magnification: 2500 X.
Figure 6	Tithonian or Neocomian specimens, slightly overgorwn. Sample 6-49.0-2-1, 88-89 cm (18 m). Magnification: 4000 X.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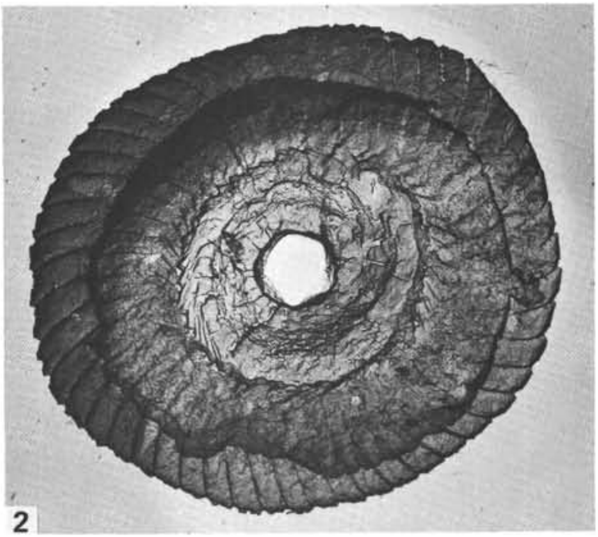
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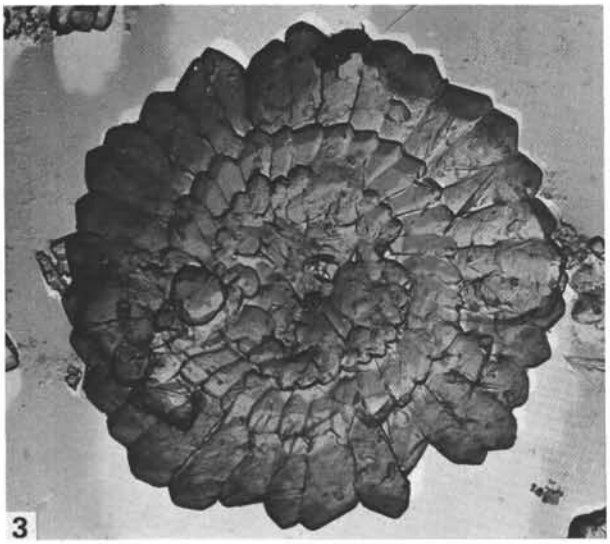
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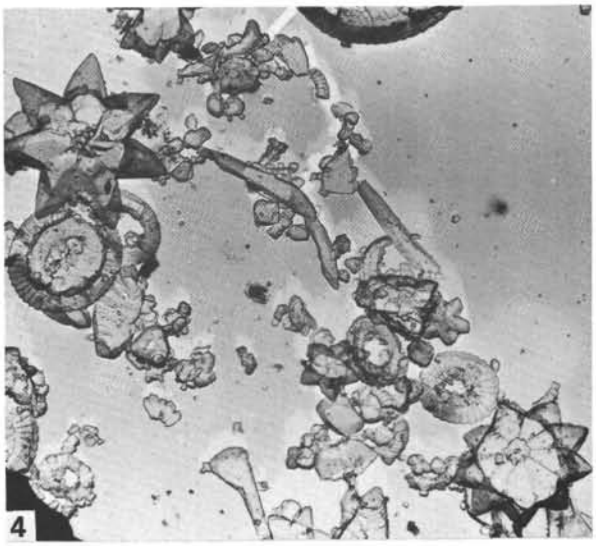
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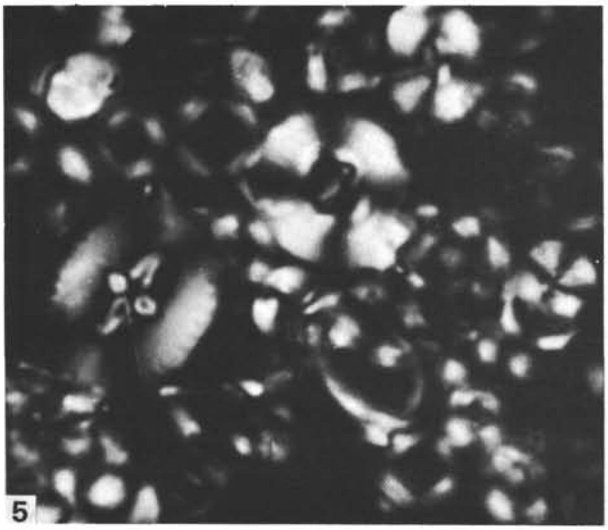
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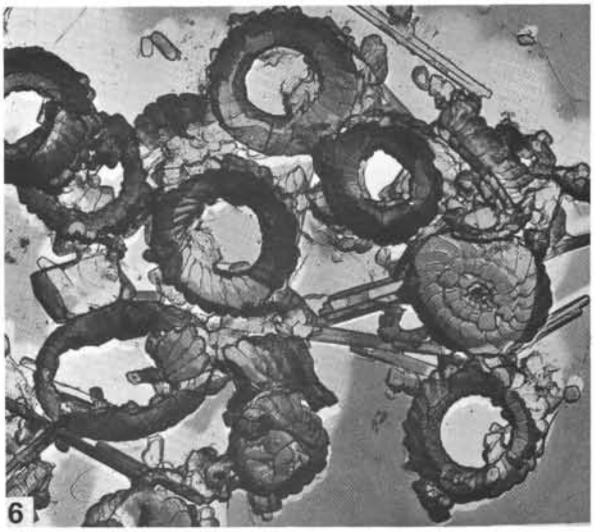
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Figure 3 shows a plot of the relative abundance of the three major microfossil groups at each site, averaged per epoch for the Cenozoic and per half period for the Cretaceous, against the depth of water at the site. Certain sites have been omitted when nearby sites convey the same information, for example, Site 47 is representative of the age and type of microfossils and water depth found at Site 48.

Abundance is a result of preservation, and foraminifera are "common," meaning they are relatively abundant, in all age samples from sites in less than 4000 meters of water; "sparse" in Tertiary samples from sites between 4000 to 5000 meters of water; "absent" in Tertiary samples at sites in gerater than 5000 meters of water. Cretaceous samples, however, do not follow this pattern. Foraminifera are abundant, as are calcareous nannoplankton, in samples at most sites deeper than 4000 meters in the northwest Pacific Basin (Sites 45, 49, 50 and 51). Sites 52 and 59, which occur in about 5500 meters of water, yielded brown clay without foraminifera for Cretaceous and Tertiary cores, indicating sedimentation below the calcite-compensation depth. Why foraminifera are preserved in Cretaceous samples from Sites 45 and 51, which occur in abyssal depths comparable to Sites 52 and 59, is not clear. One likely explanation is that the sites were shallower in the Mesozoic, and subsidence of the order of 1000 meters or more has occurred since the early Tertiary. This assumes, of course, that there has not been significant change in the compensation depth with time.

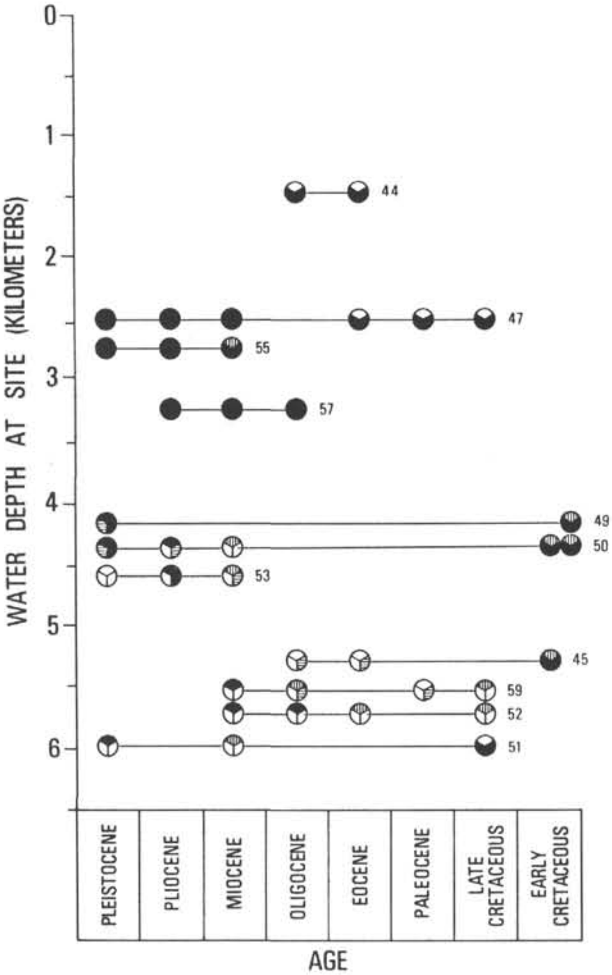

Figure 3. *Relative abundance of microfossils compared to geologic age and water depth at drilling sites of Leg 6, northwestern Pacific Ocean. Upper sector of symbols refers to radiolarians, lower left to foraminifera, lower right to nannoplankton. Solid sector indicates that the group is common; shaded, sparse; blank, rare or absent. Asterisk indicates presence of chert.*

Estimates for the Philippine Basin are less precise than for areas with carbonate-rich samples because of the smaller number of foraminifera per sample (foraminifera have been diluted by an increase in volume of pyroclastic material) and the concentration of foraminifera in layers in the cores. Some samples do not contain larger calcareous fossils, although adjacent samples do. The absence of foraminifera in such samples is believed to be a result of increased volcanic sedimentation and not removal of the fossils by solution or other means.

Neogene foraminifera are generally in a very good to excellent state of preservation. Most of the samples have only a small number of broken specimens, which can be attributed to coring or sample preparation, and, except for these, the preservation looks like that of Holocene foraminifera. In the Philippine Basin, in cores from Site 54, some layers contain only small numbers of normal adult-sized specimens. This may be due to a combination of sedimentation and preservation factors, although ecology cannot be ruled out. Small specimens may fit in the voids between relatively large irregular ash fragments, whereas adult-size foraminifera would be in point contact with the adjacent grains and likely to be broken or crushed during compaction, preventing identification. Except for broken individuals and the absence of thin delicate species, the few foraminifera in the cores from the Philippine Basin are fresh and otherwise well-preserved. There is no evidence of solution, even though the present water depth is between 4600 and 4900 meters at Sites 53 and 54.

Obvious traces of solution in Neogene foraminifera, excluding samples from sites in water depths at or below the calcite-compensation depth (Arrhenius, 1963; Peterson, 1966) is confined to the lowest core at Hole 55.0 and to the lower part of Core 6 and the top of Core 7 at Hole 47.2. Both of the latter are Miocene, but this may be coincidental. Planktonic foraminifera in Hole 55.0, Core 14, contain holes in the initial chambers and the adult chambers (less than 1 per cent), and about 1 per cent of the shells are broken at the last chamber. Most of the broken specimens involve small fragile species or species with a low overlap between chambers. Few tests seem to be broken across the sutures, a sign that the fossil was not weakened by solution before it broke. The situation in Hole 47.2, Cores 6 and 7, is different, although the causes of shell destruction are probably the same. The cores in question at 47.2 span an unconformity that brings Upper Miocene sediment into contact with Middle or Lower Eocene. A mottled dark-brown clay with burrows occurs at the contact, and calcareous chalk ooze occurs above and below the unconformity. The foraminifera directly adjacent to the unconformity are less well-preserved than those higher in the hole, numerous specimens of very large benthonic foraminifera occur, and ratios of planktonic to benthonic specimens are low. About a third or more of the planktonic foraminifera from Sections 2 and 3 of Core 6 are broken (the core is incomplete and Sections 4, 5 and 6 were not recovered). Some of the breakage may be due to sediment disturbance during drilling, but the fact that the breakage is greatest at the unconformity suggests that part is due to other causes. Specimens from the lower part of Section 3 and the core-catcher sample are chalky and contain holes indicative of solution. Specimens from the upper part of Core 6 are fresh in appearance and without holes. The foraminifera from the top of Core 7, which apparently contains down-hole slump from the section drilled in the bottom of Core 6, are very similar in preservation to those from the core catcher at the bottom of Core 6.

Paleogene foraminifera were recovered from the Shatsky Rise (Hole 47.2) and the Horizon Ridge (Hole 44.0). Relative to Neogene microfossils they are less well-preserved, but the overall condition of the foraminifera can still be characterized as very good to excellent. Evidence of solution can be found in all of the samples except for Hole 47.2, Core 11. As in the Holocene and Pleistocene, the effects of solution are taxonomically selective, and, whereas no precise species-solution rankings were made, the authors' impression is that keeled species like *Globorotalia velascoensis, G. marginodentata* and similar taxa are the least resistant, the acarininids are the most resistant, with the majority of the globigerines being intermediate. In samples from Hole 47.2, Cores 8, 9 and 10, the keeled species with acute margins account for 90 per cent or more of the chalky specimens and those with holes in the initial chambers. In the same samples, species of *Acarinina* and globigerines were unaffected, and even delicate-appearing surface spines are preserved intact. The lack of large globorotalids with acute margins in the lower Danian samples of Core 11 may account for the better condition interpreted for the fauna.

Evidence of solution can be detected on the foraminifera in all the Cretaceous samples, and the evidence is abundant for samples from Cores 12 and 13 at Site 47 and samples from Sites 49 and 50. In general, the pattern of preservation and selective solution is similar to that for Cenozoic foraminifera. Overall, the preservation of the Cretaceous microfossils, except for the Neocomian species, can be said to be very good, and many specimens possess intact tegilla and other delicate structures often missing in fossils from terrestrial outcrops.

Radiolaria

Evidence of variable preservation of Cenozoic radiolarians generally is expressed as removal of delicate forms rather than as partial destruction of individuals, although this problem is as yet little studied. Obvious diagenetic effects, then, take the form of increasing dominance of robust skeletons with increasing age. Precipitation of chert from silica-enriched interstitial solutions presumably is the eventual result of high post-burial dissolution rates. Outlines of radiolarian skeletons can frequently be observed in chert, but diagenetic effects transitional between well-preserved radiolarian assemblages and chert have not been noticed during studies not designed for this purpose.

Mesozoic radiolarians from Leg 6 are generally poorly preserved, showing alteration of the original opaline silica to more crystalline forms which also fill the void spaces of the original skeleton. Silica mobilization is again evidenced by radiolarian-bearing chert that is often associated with the altered specimens.

Skeletons of micro-organisms are also affected by dissolution during descent through the water column and residence at the sediment-water interface before burial. There is an apparent relationship between silica preservation and relative bottom depth in terms of which Leg 6 results may be discussed. Although samples from the single site in the Horizon Ridge area, Site 44, contain abundant calcareous microfossils, no siliceous ones were found. Assuming as one possibility that siliceous-shelled plankton were produced in abundance approximately equal to calcareous-shelled forms as proposed by Cifelli and Sachs (1966), the silica could have been dissolved, leaving a carbonate-rich sediment. This site can then be assumed to lie above what may be termed a silica-compensation level. The silica-compensation level is defined as a level *below which* the rate of supply of siliceous skeletons exceeds the rate of dissolution. It is implicit in the work of Berger (1968b), who showed that the rate of silica dissolution is more rapid above about 2000 meters in the North Pacific, where concentrations of silica are relatively low and temperatures high. It thus operates inversely to the better known calcite-compensation level, in that skeletal material above the level rather than below it is removed. It is not, therefore, to be confused with a hypothetical level *below* which silica might be rapidly dissolved; such does not appear to exist (Riedel, 1959).

Although the concept of a silica-compensation level warrants further discussion, documentation and experimental verification, it is proposed here that sediment rich in calcareous pelagic remains but lacking siliceous tests, such as that encountered at this site, may have formed above such a level. Pelagic sediment lacking both siliceous and calcareous microfossils, on the other hand, generally occurs on the deep-ocean floor beneath oceanic areas of low organic productivity (the central water masses) where residence time at the water-sediment interface is sufficient that both types of material are dissolved.

The concept of a silica-compensation level thus provides us with an additional reference plane by which to discuss the depth of deposition of pelagic sediment on the basis of its content of skeletal mineralogical types. (1) Sediment containing only calcareous forms would occur above the silica-sompensation level; (2) that containing both siliceous and calcareous tests would occur between the silica and calcite-compensation levels; (3) and, that bearing only siliceous remains would form below the calcite-compensation level. It must be emphasized, however, that a constant relation between the two compensation levels and water depth cannot be assumed. The depth of both levels is related, but in different ways, to the circulation of subsurface water masses (Berger, 1970). For example, the silica-compensation level is much deeper in the Atlantic Ocean, which is generally warmer and relatively deficient in dissolved silica.

Calcareous ooze on the Horizon Ridge ranges in age back to the middle Eocene, implying that the area was above the silica-compensation level since that time. Chert near and at the bottom of the middle Eocene calcareous sediment indicates either that silica was then preserved because the area was below the silica-compensation level and was recrystallized in place, or that original silica in the carbonate sediment became mobilized later and was redeposited at this level as chert beds.

Radiolarians are well-preserved in sediment ranging in age from Quaternary back through approximately middle late Miocene on the Shatsky Rise. In cores of older sediment, siliceous microfossils rapidly disappear while calcareous forms are preserved. Poorly preserved (quartz-infilled) Cretaceous or Upper Jurassic radiolarians are found in lower horizons. During the Lower and Middle Tertiary, the silica-compensation level was probably deeper, relative to present sea level.

Siliceous skeletons are generally well-preserved in Middle and Upper Miocene volcanogenic sediment from the Philippine Basin. Few samples of younger age were obtained. Samples from deeper horizons in Hole 53.0, dated early Oligocene to early Miocene on the basis of relatively poor calcareous nannofossil content, contained rare and relatively poorly preserved radiolarians of late Miocene age suggesting drilling contamination. No convincing evidence, based on differential dissolution of carbonate and silica, or of regional change of compensation level can be inferred from these samples. Preservation of siliceous microfossils is as would be expected at present-day ocean depths.

Radiolarians as well as calcareous microfossils are well-preserved in Caroline Ridge sediment ranging in age from late Oligocene (the oldest found in the area) through Middle Miocene. Samples rich in calcareous skeletons younger than Middle Miocene contain redeposited older radiolarian species with only occasional specimens of younger age. From this evidence it appears that sediment was deposited at depths below the silica-compensation level for the early Miocene. Early Middle Miocene assemblages contain some species normally restricted to the early Miocene. Late Middle Miocene sediment contains only orosphaerid fragments (the most solution-resistant radiolarian remains) actually diagnostic of that age. At least part of the remaining assemblage appears to be reworked. Sediment above these radiolarian-bearing upper Middle Miocene deposits contains no radiolarians, but Lower Miocene species begin to appear again in higher horizons considered lower Upper Miocene on the basis of calcareous microfossils.

Although reworking could account for the appearance of Lower Miocene species in Middle Miocene samples, it is suggested that some tectonic disturbance took place at about this time exposing Lower Miocene strata from which the fossils were derived. A comparable state of preservation of *in situ* and derived specimens supports this view. During the late Middle Miocene, uplift to depths as shallow as the present appears to have enhanced dissolution of the radiolarians of that age, while the sediment continued to receive contributions of early Miocene species from nearby outcrop exposures. This same early Miocene assemblage then persists as essentially the only preserved radiolarian contribution to sediments from late Miocene through the Pleistocene and probably the Holocene. Preservation of older fossils in sediment lacking contemporaneous fossils may be attributed to: (1) the older assemblage consisting of more resistant forms, or (2) the older fossils having been rapidly buried.

Radiolarian skeletons deposited on the deep ocean floor are slowly dissolved unless they are removed from the sediment-water interface relatively rapidly be deposition of additional material. In areas remote from large supplies of terrigenous or volcanic sediment, then, preservation depends chiefly on organic productivity in the overlying water. This relationship is supported by the results from this cruise leg. Abyssal Pacific sediment at Sites 45 and 46, underlying the poorly productive Central Water Mass contains no Cenozoic Radiolaria. Mesozoic forms at Site 46 were deposited when oceanographic conditions and/or the location of that part of the ocean floor may have been quite different from today. Site 59, under a more productive region, contains fairly well-preserved siliceous microfossils.

REGIONAL CORRELATION

Calcareous Nannoplankton

Present knowledge concerning the calcareous-nannoplankton assemblages of the Pacific region is limited. Assemblages from California are probably best known owing to the work of M. N. Bramlette of Scripps Institution of Oceanography, who has published descriptions and correlations for Upper Paleocene, Lower and Middle Eocene, Lower and Middle Miocene.

Most studies of samples from such areas as Hawaii, Japan, Saipan, the Philippines, Indonesia and New Zealand are short reports based on a small number of samples (Figure 5). The oldest nannoplankton-bearing strata thus far reported from land areas of the Pacific region are Upper Cretaceous–Campanian from California (Bukry and Kennedy, 1969). Older Cretaceous strata in California and Japan potentially containing calcareous nannoplankton have not yet been assayed.

Assemblages from the Upper Paleocene and Lower Eocene of California belong to the same sequence of zones as those represented in Leg 6 cores from the northwestern Pacific: *Discoaster multiradiatus* Zone, *Discoaster diastypus* Zone, *Marthasterites tribrachiatus* Zone and *Discoaster lodoensis* Zone. A comparison of the floral lists from both areas does reveal certain differences, however. The Leg 6 samples from an open-ocean depositional environment contain no specimens of *Braarudosphaera* or *Micrantholithus.* Likewise, *Rhabdosphaera* and *Helicopontosphaera,* which are common in the Eocene assemblages of California, are missing from the open-ocean assemblages. This same relationship occurs in upper Paleocene and lower Eocene assemblages recovered in the South Atlantic Ocean during Leg 3 (Bukry and Bramlette, 1970). Since the zonation for nannoplankton-bearing strata can be based on the whole assemblage, other more cosmopolitan genera, such as, *Chiasmolithus, Coccolithus, Discoaster, Fasciculithus, Heliolithus* and *Zygodiscus,* are used to subdivide this interval in open-ocean facies as well as in shelf facies.

With the excellent open-ocean core sequences of nannoplankton-rich sediment now available for study from the Pacific as a result of the Deep Sea Drilling Project, the stratigraphic and paleoecologic usefulness of this fossil group for correlation of circum-Pacific sections should be greatly enhanced.

Planktonic Foraminifera, Mesozoic

Cretaceous planktonic foraminifera provide one of the best means for long-distance correlation. Dependence on this group alone, however, limits the number of areas for which precise comparisons are possible, despite the fact that Cretaceous strata essentially encircle the Pacific Basin. Correlation between the Leg 6 cores and many areas adjacent to the Pacific Ocean is imprecise owing to various factors: (1) lack of sufficiently detailed study of the Mesozoic planktonic foraminifera; (2) impoverished assemblages resulting from poor preservation or ecologic conditions; and, (3) lack of favorable facies (a major problem, especially in the thick flysch deposits of North and South America).

An attempt at a general correlation between stratigraphic sections of the deep northwestern Pacific and California, Japan, the west Pacific, and Australia seems worthwhile in order to illustrate (1) the status of Cretaceous biostratigraphic investigation based upon planktonic foraminifera, (2) regional variation in the distribution of planktonic assemblages in the Pacific region, and (3) relations between the oceanic sequence and contiguous continental and island sequences.

The correlations given in Figure 6 imply in some cases greater precision than actually exists. Where planktonic foraminifera are absent or insufficient to establish correlation, ammonites, larger foraminifera, and superpositional relationships provide the evidence for positioning formations in the chart. For completeness, comparisons for Lower Cretaceous strata are also shown in the correlation chart, but, as they are based on relationships supplied by other than planktonic foraminifera they will not be discussed in detail.

California

The planktonic foraminiferal biostratigraphy of California and adjacent areas has been recently discussed by Martin (1964), Marianos and Zingula (1966), Takayanagi (1965), Sliter (1968), Douglas (1969a,b), and Douglas and Sliter (1966). The faunas described by these workers can be distinguished from Tethyan faunas by the absence of species restricted to low latitudes and by a difference in the relative abundance of certain species groups, such as, the *Hedbergella* species. These differences persist at almost all stratigraphic levels, but the "provincialism" is most distinct in the middle Upper Cretaceous (Douglas and Sliter, 1966). California assemblages from these horizons contain fewer species and sometimes different species than those present in the northwestern Pacific.

SERIES or STAGE	CAROLINE RIDGE					PHILIPPINE BASIN					SHATSKY RISE					HORIZON RIDGE					ABYSSAL BASIN				
	CORE	1	2	3	4	CORE	1	2	3	4	CORE	1	2	3	4	CORE	1	2	3	4	CORE	1	2	3	4
PLEISTOCENE	HOLE 55.0										HOLE 47.2														
	1	A	A	A	B						1	A	A	A	B										
											2	A	A	A	B										
PLIOCENE	HOLE 55.0										HOLE 47.2														
	2	A	A	A	C						3	A	A	A	B										
	3	A	A	A	B						4	A	A	C	D										
											5	A	A	A	C										
MIOCENE	HOLE 55.0					HOLE 53.1					HOLE 47.2														
	5	A	A	B	C	2	A	A	A	B	6	C	A	D	F										
	7	A	A	A	C	3	A	A	A	B															
	10	A	C	B	B	HOLE 54.0																			
	11	A	A	A	B	2	A	A	A	B															
	12	A	A	A	B	3	A	A	A	B															
						4	A	A	A	B															
OLIGOCENE	HOLE 55.0															HOLE 44.0					HOLE 46.0				
	13	A	A	A	B											1	B	B	B	C	1	DISSOLVED			
	14	A	B	B	B																				
EOCENE											HOLE 47.2					HOLE 44.0					HOLE 46.0				
											7	B	C	A	C	2	C	C	B	C	2	DISSOLVED			
											8	C	C	B	C	3	C	B	B	C					
																4	D	D	D	E					
PALEOCENE											HOLE 47.2														
											9	B	C	B	B										
											10	A	B	A	C										
											11	A	A	A	B										
MAESTRICHTIAN											HOLE 47.2														
											12	F	F	E	F										
											13	F	E	D	E										
											14	F	E	D	E										
SANTONIAN and CONIACIAN																					HOLE 51.0				
																					3	A	B	B	C
CENOMANIAN																					HOLE 45.1				
																					3	B	B	C	C
NEOCOMIAN											HOLE 49.0														
											2	A	A	D	E										
											HOLE 49.1														
											2	A	A	D	E										
											HOLE 50.0														
											2	A	A	D	C										

Figure 4. *Preservation of foraminifera in Leg 6 cores showing percentage of specimens in the following categories shown in numbered columns: (1) shells with a chalky appearance; (2) shells with holes in the first 1-6 chambers; (3) shells with holes in the adult chambers; (4) broken shells. A = 0%; B = trace to 1%; C = 1-5%; D = 5-15%; E = 15-35%; F = greater than 35%.*

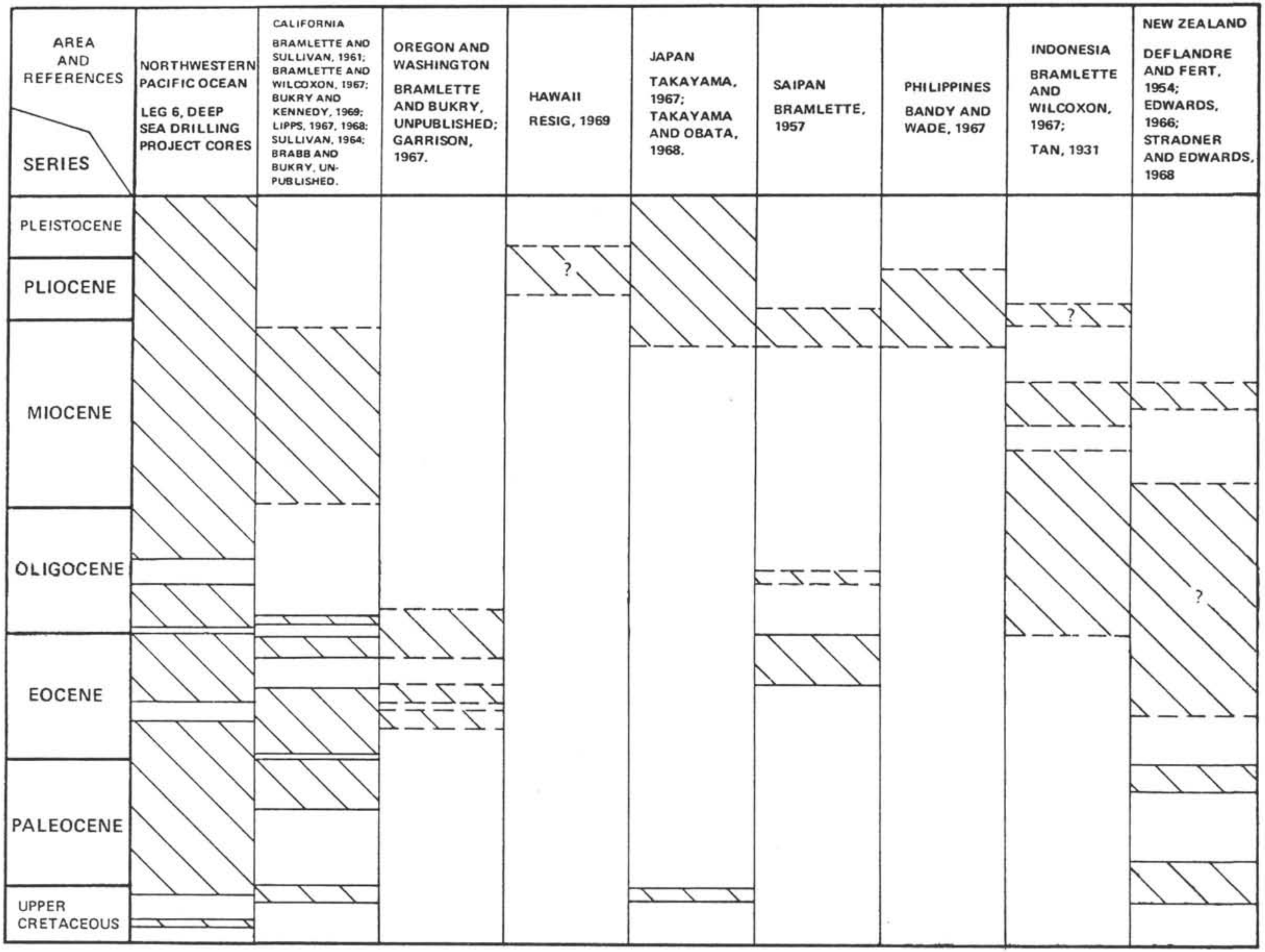

Figure 5. *Known coccolith-bearing rocks from land areas of the Pacific region compared with a composite section from the northwestern Pacific sea floor.*

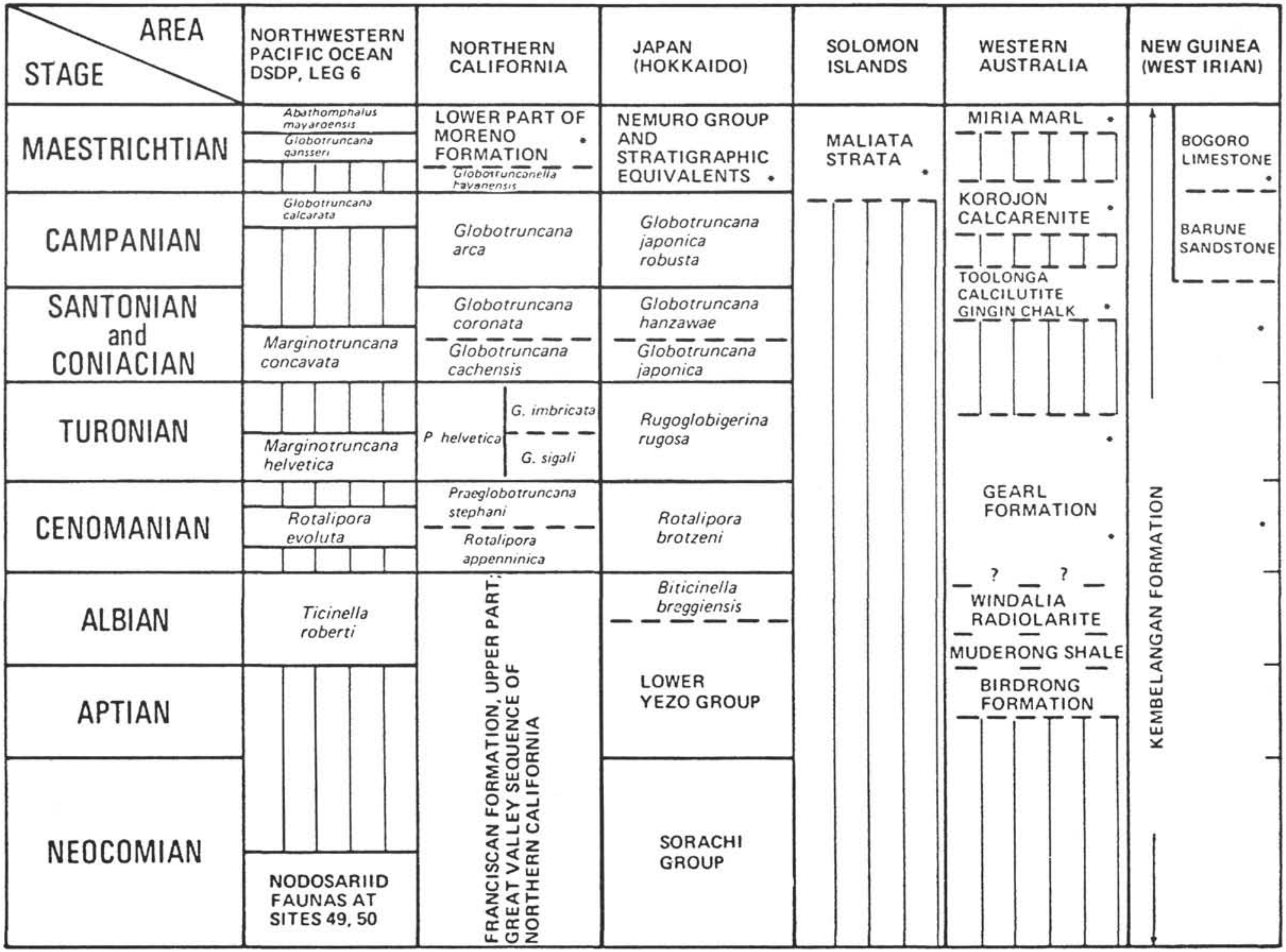

Figure 6. *Regional Cretaceous correlations within the Indo-Pacific and Pacific regions, based mainly on planktonic foraminifera. For regions where biostratigraphic zones have been defined, the zonal species are indicated, elsewhere formations are shown. Asterisks indicate levels in formations that contain planktonic species correlative with strata sampled in the northwestern Pacific by Leg 6, Deep Sea Drilling*

Albian planktonic species occur in the thick clastic formations of the Great Valley sequence, but few have been studied in detail. Marianos and Zingula (1966) report *Ticinella roberti, Hedbergella planispira, H. trochoidea, Planomalina buxtorfi, Rotalipora ticinensis* and *R. tehamaensis* (= *R. greenhornensis;* Douglas, 1969b) in the Upper Albian. The first four microfossils occur in the samples from Site 51 and *Ticinella* sp. cf. *T. roberti* and *Hedbergella trocoidea* are admixed in samples from Site 50. *Planomalina buxtorfi* is present at Site 51 and reworked into the Miocene sediment at the site-selection ship *Argo's* Core 20P (24° 0.9′N, 178° 30.2′W), but the species was interpreted as Cenomanian rather than Albian because of its more common occurrence in the Cenomanian. With the exception of *Hedbergella trocoidea* (Sigal, 1966), the species is common between the northwestern Pacific and California are indicative of the upper part of the stage. Another species that is frequently found in deposits of this age is *Ticinella breggiensis,* which is reported from the Shatsky Rise (Ewing and others, 1966) and Japan (Asano and Takayanagi, 1965) but is unrecorded from California.

The *Rotalipora evoluta* Zone in the northwestern Pacific (Sites 45, 51) can be correlated with the *R. appenninica* Zone in northern California (Douglas, 1969). Species in common include *Rotalipora evoluta, R. greenhornensis, Planomalina buxtorfi, Praeglobotruncana delrioensis* and several species of *Hedbergella.* The rotaliporids occur in the lower or lower middle Cenomanian, depending upon whether a two-fold or three-fold subdivision of the stage is used. Typical assemblages from the Great Valley sequence contain an impoverished assemblage compared with the northwestern Pacific, particularly in numbers of foraminifera per sample. However, the Calera Limestone Member of the Franciscan Formation south of the San Francisco area, which is lower middle Cenomanian (Loeblich and Tappan, 1961), contains a faunule that is very similar to the Pacific samples. Comparison of the three assemblages, northwestern Pacific, Calera Limestone, and Great Valley sequence, provides an indication of the faunal changes that can occur in different deep-water depositional environments within the same ocean basin.

Upper Cenomanian species that are widespread in California, such as *Rotalipora cushmani* and *Praeglobotruncana stephani,* are as yet unrecorded in the deep Pacific. *Praeglobotruncana helvetica* and *G. sigali* occur in the basal part of the *P. helvetica* Zone in central and northern California (Douglas, 1969a,b). These species occur as reworked fossils in *Argo* Core 20P and were probably derived from lower Turonian deposits on the nearby western end of the Hawaiian Ridge. No other Turonian microfossils are known from the Pacific.

Comparison of the *Marginotruncana concavata* Zone at Site 51 with lower Senonian zones in California is based upon the common occurrence of *M. pseudolinneiana, M. coronata* and *Archaeoglobigerina* sp. The first two species range from the upper Turonian to Santonian and do not provide a means for precise correlation. The exact stratigraphic relationship of the *M. concavata* Zone of the Pacific and other Tethyan areas to either the *Globotruncana cachensis* Zone or the *G. coronata* Zone is unclear. Ammonites suggest that the *G. cachensis* Zone spans the Coniacian and possibly lower Santonian and is therefore more nearly a time equivalent of the zone in Tethyan areas.

Fairly diverse Campanian and lower Maestrichtian planktonic faunas are recorded from California in northwest Mexico (Sliter, 1968); but, microfossils of this age were not cored during Leg 6, except for a few reworked species in the *Argo* core. These included *Globotruncana calcarata,* which is restricted to the upper Campanian (Pessagno, 1967). Bandy (1967) reports an occurrence of this species in southern California, but it does not occur in the outcrop sections in San Diego County (Sliter, 1968) or in the northern part of the state (Martin, 1964; Douglas, 1969a,b).

The biostratigraphic relation of Maestrichtian strata in California is poorly understood because of the endemic aspect of the ammonite faunas and the lack of stratigraphically diagnostic species among the planktonic foraminifera (Matsumoto, 1959; Douglas and Sliter, 1966). The better known fossil horizons that bear planktonic foraminifera appear to be early Maestrichtian in age and thus older than any Maestrichtian assemblages recovered in the northwestern Pacific. An exception may be an isolated faunule on San Miguel Island (R. G. Douglas, unpublished), where a single sample yielded *Globotruncanella havanensis, Globotruncana* sp. cf. *G. patelliformis, Racemiguembelina fructicosa, Pseudotextularia deformis* and *Gublerina cuvillieri,* which is middle Maestrichtian (*Globotruncana gansseri* Zone) or younger and probably overlaps the lowest samples from Deep Sea Drilling Project Hole 47.2, Core 14, and Hole 48.2, Core 3. In the San Joaquin Valley a complete sequence of strata extends from the Campanian to Lower Paleocene, but the top of the Cretaceous is represented by a noncalcareous facies (Martin, 1964). Recently radiolarians but no foraminifera were recovered from the shales in the upper Moreno Formation, and these have been dated as Upper Maestrichtian (Foreman, 1968). Beds equivalent to the sediments in Hole 47.2, Cores 12, 13 and 14 and Hole 48.2, Cores 1, 2 and 3 are present in California but lack correlative fossils.

Japan

Cretaceous planktonic foraminiferal faunas in Japan have been studied by Asano (1950), Takayanagi and

Iwamoto (1962), Takayanagi (1960), and Yoshida (1958; 1963) and summarized by Asano and Takayanagi (1965). Nearly all of the studies have been undertaken on the northern island of Hokkaido; the planktonic foraminifera from Cretaceous marine strata on the other islands remain to be investigated.

Biticinella breggiensis, Hedbergella trocoidea, H. trocoidea yezoana, H. delrioensis, and *H. washitensis* occur in the middle Yezo Group of central Hokkaido and are correlated with the upper Albian of Europe (Takayanagi and Iwamoto, 1962). Despite the apparent overlap in age between the *Biticinella breggiensis* Zone and the admixed Lower Cretaceous assemblages from the Shatsky Rise (Sites 49, 50, 51) and the Lamont-Doherty core (Ewing and others, 1966), the faunal similarity between the two areas is slight. The species identified by Takayanagi and Iwamoto as *H. delrioensis* and *H. trocoidea,* judged by their illustrations, are different from the Leg 6 species, and *H. washitensis* is absent in the Shatsky Rise cores. The faunal differences, possibly ecologic, prevent precise comparison.

The *Rotalipora brotzeni* Zone in Hokkaido contains the first appearance of *Praeglobotruncana stephani, Rotalipora brotzeni* (= *R. greenhornensis;* Loeblich and Tappan, 1961), and *R. montsalvensis minor* and based on these species is Cenomanian in age (Asano and Takayanagi, 1965). In North America and Europe this association of species is restricted to the upper part of the stage, or basalmost Turonian (Moorkens, 1969). It seems likely that the Japanese assemblage is younger than the microfossils from either Site 45 or the mixed Cenomanian species at Site 51.

Asano and Takayanagi (1965) report a total of eight species in the four zones representing the Turonian, Santonian to Coniacian, and Campanian. No planktonic foraminifera have been recovered from Maestrichtian strata in Hokkaido (Yoshida, 1961; Asano and Takayanagi, 1965). Of the eight species, three–*Rugoglobigerina rugosa, Globotruncana fornicata,* and *Heterohelix globulosa* (= *H. striata;* Stenestad, 1969)–are recorded under the same names as species from the northwestern Pacific, but they appear to represent different taxa. The Turonian and Santonian to Coniacian occurrences of *R. rugosa* and *G. fornicata* are probably *Hedbergella* sp. and *Marginotruncana pseudolinneiana,* respectively, based on descriptions given in Takayanagi (1960, 1965). Associated species in Japan, *Globotruncana japonica* and *G. hanzawae* appear congeneric and perhaps conspecific with *M. pseudolinneiana,* but collectively these species and those mentioned above do not offer a strong basis for precise correlation with the assemblages at Site 51 or the Campanian species reworked in *Argo* Core 20P.

In summary, it is difficult to relate the assemblages described from Hokkaido to those recovered by Leg 6 except in a gross way because of the impoverished nature of the Japanese fauna and the taxonomic differences. At the present time, correlation is possible only at the stage level, and zonal correlations await the discovery of further planktonic foraminifera.

West Pacific

Solomon Islands

Fine-grained foraminiferal limestone on the island of Malaita, on the Pacific flank of the Solomon Islands group, contains Radiolaria, radiolarian chert, and several species of Cretaceous planktonic foraminifera (Coleman, 1966). Species distinguished by Coleman in thin-section studies of the limestone include *Globotruncana* similar to the species *G. arca, G. lapparenti, G. havenensis,* questionable *Heterohelix,* and several globigerine-shaped taxa, possibly in the genus *Rugoglobigerina.* Based on the tentative identifications, a late Senonian, Campanian or Maestrichtian age is suggested for the assemblage (Coleman, 1966). If the assemblage is Upper Senonian, it is roughly correlative with the Shatsky Rise assemblage and mid-Pacific assemblage of Hamilton (1953). However, whereas there is no doubt of Cretaceous age of the species in the limestone, they may be older than suggested. Comparison of the figured profiles (Coleman, 1966, Plate 8) with thin sections of oriented free specimens, admittedly a difficult task that does not always yield unequivocal results, reveals a remarkable similarity to upper Cenomanian and lower Turonian species (for example, compare Plate 8, Figure 15 to *Rotalipora cushmani;* Figures 3 and 4 to *Marginotruncana coronata,* Figures 7 and 9 to *M. pseudolinneiana,* Figure 8 to *M. helvetica,* and Figures 1 and 2 to *M. biconvexa* contained in Brönnimann and Brown, 1956; Pessagno, 1967).

The significance of the Solomon Islands Cretaceous is not so much a precise correlation within the Pacific as the occurrence of an oceanic assemblage of Cretaceous planktonic foraminifera at this geographic location. Riedel and Funnel (1964) report reworked Cretaceous fossils (Radiolaria) at latitude 9 S, not far from the Solomon Islands. At the present time, these two occurrences are the only known Cretaceous fossils from this region of the southern hemisphere, a region that otherwise is known only to contain Cenozoic sediments.

New Guinea

Cretaceous marine strata are known from several regions in New Guinea, including West Irian and Papua (Visser and Hermes, 1962; Hermes and Schumacher, 1961; Glaessner, 1952, 1960; Rickwood, 1955). Generally, details concerning the planktonic foraminifera from these areas are lacking, and correlation is based on or supplemented by age determination from other microfossils. A few details can be mentioned.

Visser and Hermes (1962) report keeled planktonic species from indurated pelagic sediment in the central and northern New Guinea provinces of West Irian. They recognize three subzones of the *Globotruncana* Zone: *Globotruncana appenninica* (= *Rotalipora appenninica*), *G. lapparenti* and *G. stuarti.* These assemblages suggest Cenomanian, lower Senonian and Maestrichtian, respectively, and larger foraminifera indicate the presence of Campanian and Maestrichtian strata. Thus, parts of the section are equivalent to sediment in the northwestern Pacific, but the zonal assemblages remain to be described in New Guinea.

In Papua, Maestrichtian species, including *Pseudotextularia elegans, P. varians* (= *Racemiguembelina fructicosa*), *Planoglobulina acervulinoides, Globotruncana arca, G. stuarti, G. contusa,* and *G. conica* are known from the Bogoro Limestone in the Port Moresby district (Glaessner, 1960; McGowran, 1968). Rickwood (1955) found a similar faunule to the north in the Mango Marl and reported, in addition to the above species, *Ventilbrella eggeri* (= *Planoglobulina multicamerata*). These species definitely establish the Maestrichtian age of the sediments and suggest correlation to the assemblages from the late Maestrichtian sediment on the Shatksy Rise. Unfortunately, the species are insufficient to delimit which zones of the Upper Maestrichtian are present in Papua (perhaps both). Future investigation in New Guinea offers the possibility that a relatively complete Cretaceous sequence partly developed in pelagic facies, will be recognized.

Australia

Late Cretaceous marine strata occur in northern, southern and western Australia, but it is only in the Carnarvon and Perth Basins along the western margin of Australia that abundant planktonic foraminifera are known. The planktonic species from these strata have been discussed by Edgell (1957), Belford (1958; 1960) and McGowran (1968), and they can be readily correlated with the assemblages in the northwestern Pacific and Tethyan regions.

The oldest planktonic foraminifera described are Cenomanian from the Gearle Formation. Older formations, based on benthonic foraminifera and molluscs, are present in boreholes near Carnarvon (Edgell, 1957; Belford, 1958). Belford argues for an Albian correlation of *Globotruncana (Praeglobotruncana) delrioensis* (= *P. delrioensis*) and benthonic foraminifera from the lower part of the Gearle Formation, but that planktonic species is now considered a Cenomanian fossil (Loeblich and Tappan, 1961; Pessagno, 1967). The same species occurs abundantly at Site 45.

Planktonic foraminifera are better represented in the upper part of the Gearle Formation, which is in part Upper Cenomanian based on *Globotruncana stephani* and *G. stephani turbinata* and *Rotalipora turonica* (= *R. cushmani*) and in part Turonian. The Turonian beds include species of the *Marginotruncana helvetica* Zone and double-keeled taxa, such as, *Globotruncana lapparenti* and *G. marginata* (Edgell, 1957; Belford, 1958). Belford suggests that the entire assemglabe is lower Turonian, but that the double-keeled species indicate the middle to upper Turonian is also represented. Offshore and southwest of Perth, lower to middle Turonian species have been found in a core raised on the Naturaliste Plateau (latitude 33° 40'S, longitude 112° 40'E), including: *Praeglobotruncana helvetica, P. biconvexa, P. stephani, Hedbergella portsdownensis, Globigerinelloides caseyi* and *Schackoina multispenata* (Burckle and others, 1967).

A regression began in the Carnarvon Basin, possibly in the Perth Basin in the Turonian, and lasted through the Coniacian. The Toolonga Calcilutite, Gingin Chalk, and stratigraphic equivalents span the Santonian and lower Campanian (Belford, 1958). *Marsupites* and *Uintacrinus* from the lower part of the Toolonga and from the Gingin Chalk provide a tie with the classical Santonian sections in Europe. These fossils indicate that the strata are probably younger than the *Marginotruncana concavata* Zone at Site 51, and this idea is strengthened by the presence of *Globotruncana bulloides, G. cretacea,* and species of *Neoflabellina* and *Bolivinoides,* which are considered Upper Santonian in the Gulf Coast region (Cushman, 1946; Pessagno, 1967). It is interesting to note that *Globotruncana fornicata* is absent from these formations, as in rocks of the same age in California, although there is a stronger Tethyan aspect to the microfaunas than in the northwestern Pacific. Santonian microfossils have been reported from the overlying Korojon Calcarenite, but no evidence for a Santonian age is found in the foraminiferal assemblages (Belford, 1958).

Campanian planktonic foraminifera from western Australia are characterized by rather undiagnostic cosmopolitan species, similar to associations in California (Douglas, 1969; Sliter, 1968). Belford lists *Globotruncana arca, G. fornicata, G. marginata, G. lapparenti, G. globigerinoides* (= *G. cretacea*) and *G. paraventricosa.* There are some species in common with the northwestern Pacific.

The Miria Marl contains one of the few occurrences of the *Abathomphalus mayaroensis* Zone in the Indo-Pacific region (McGowran, 1968). In addition to the zonal index species, identified as *Globotruncana planata* by Edgell (1957), there is *G. stuarti, G. contusa, G. elevata, G. citae* (= *Globotruncanella havanensis*), and *Rugoglobigerina rotundata.* This assemblage correlates closely with the foraminifera from the Upper Maestrichtian part of Hole 47.2 and Hole 48.2.

Planktonic Foraminifera, Cenozoic

The importance of stratigraphic studies carried out in the course of Leg 6 and the stratigraphic completeness of sections of Paleogene and Neogene sediments in the area of the Caroline Ridge, Horizon Ridge, and the Shatsky Rise become especially obvious when an attempt is made to correlate to Paleogene and Neogene deposits developed on contiguous continents and islands. The ages of these contiguous deposits are interpreted in accordance with the stratigraphic scheme adopted here for subdivision of pelagic sediment of the northwestern Pacific Ocean.

Solomon Islands

Deposits of Upper Eocene, Oligocene, Miocene and Pliocene make up the Malaita Group (McTavish, 1966).

The Upper Eocene contains beds with *Globigerapsis semiinvoluta, G. index, Globorotalia cerro-azulensis* and *Pseudohastigerina micra;* the Oligocene has layers containing *Globigerina ampliapertura, G. ciperoensis, G. angulisuturalis* and *Globigerinita martini.*

The Oligocene-Miocene boundary appears to be drawn within the Alite Limestone, as the *Globorotalia kugleri* Zone according to McTavish' concept (1966) includes a part of the *Globigerina ciperoensis* Zone. Indeed, it is characterized by *Globorotalia kugleri, G. opima nana, Globigerina ciperoensis, G. angulisuturalis, G. angustiumbilicata, G. venezuelana, Globigerinita dissimilis* and *Globoquadrina dehiscens.*

The upper parts of Alite Limestone and the Suaba Chalk are assigned to the Miocene. McTavish distinguishes, from the bottom upwards: (1) beds containing *Globigerinita dissimilis, G. unicava, Globigerinoides trilobus, G. venezuelana, G. juvenilis* (analogues of the *Globigerinita dissimilis* Zone); (2) beds containing *Globigerinatella insueta, Globigerinoides trilobus, G. bisphaerica, Globoquadrina altispira, G. dehiscens, G. langhiana, Globorotalia barisanensis* (analogues of the *Globigerinatella insueta* Zone; and, (3) beds containing *Globoquadrina altispira, Globigerinoides transitoria, Sphaeroidinellopsis kochi, Orbulina* sp. McTavish correlates them to the upper part of the *Globigerinatella insueta* Zone—the lowermost parts of the *Globorotalia fohsi* Zone, that is, the boundary of lower and middle Miocene is drawn within the layers with *Globoquadrina altispira.*

Less clear is the age of beds containing *Globigerina nepenthes* and those containing *Sphaeroidinellopsis seminulina,* separated from underlying deposits by a hiatus. In addition to these two species, the beds are characterized by *Globigerina bulloides, G. apertura, Hastigerina siphonifera, Globigerinoides bollii, Globorotalia lenguaensis, G. scitula.* Deposits with the above microfauna are within the Tortonian Stage (Middle or Upper Miocene) or Messinian Stage (Upper Miocene). Pliocene is presented by the Tomba Silt, with *Pulleniatina obliquiloculata, Sphaeroidinella dehiscens, Globigerinoides conglobatus, Candeina nitida, Globorotalia puncticulata, G. inflata* and *G. truncatulinoides* (probably *G. tosaensis*).

Mariana Islands

On the Mariana Islands (Guam and Saipan), there are deposits of Upper Eocene, Oligocene, Miocene and Pliocene.

On Guam, Upper Eocene, Oligocene and Lower Miocene microfaunas were described from interlayers of sedimentary rocks among volcanic rocks (Todd, 1966). The Upper Eocene is characterized by *Hantkenina inflata, H. alabamensis, Globigerapsis index, Globorotalia centralis, G. spinuloinflata* and *G. spinulosa.* The presence of these last two species is evidence that the so-called Upper Eocene deposits include layers belonging to the Middle Eocene as well. To the Oligocene are assigned layers containing *Globigerina ampliapertura, G. gortanii, G. sellii, Globorotalia opima, Cassigerinella chipolensis* and *Chilogumbelina cubensis.* To the lower part of Lower Miocene should be assigned layers containing *Globigerinoides trilobus, Globigerinita dissimilis* and various benthonic foraminifera (Mahlac Member of the Alutom Formation).

Deposits of the upper part of the Lower Miocene on Saipan were discussed by Todd, Cloud, Low and Schmidt (1954). In a member consisting of alternating andesitic lava and tuffaceous clay, they found *Globigerinatella insueta, G. trilobus, G. subquadratus, G. bisphaerica, Globoquadrina dehiscens* and *G. altispira.*

On Guam and Saipan, Upper Miocene and Pliocene deposits also were recognized, but only summary lists of foraminifera were given for them: *Orbulina suturalis, O. bilobata, Globorotalia fohsi robusta, G. menardii, Globigerina nepenthes, Sphaeroidinellopsis seminulina, Sphaeroidinella dehiscens, Pulleniatina obliquiloculata, Candeina nitida, Globigerinoides conglobatus* and *G. sacculifera.*

The Philippines

On Luzon Island the Paleogene begins with Upper Eocene deposits (lower part of the Aksitero Formation) containing *Hantkenina* sp. *Globorotalia cerroazulensis, G. centralis, Globigerina tripartita, Globigerinatheca barri* and *Globigerinita unicava* (Amato, 1965). The upper part of this formation contains an Oligocene microfauna—*Globorotalia opima, Globigerina ampliapertura, G. angustiumbilicata* and *G. sellii.*

The stratigraphy of the Neogene deposits has been studied more thoroughly. On the islands of Luzon (Bandy, 1963a; Amato, 1965), Panay (Bandy, 1967) and Eastern Isabela (Gonzales, 1960), formations which bear different names, contain these deposits.

Based on planktonic foraminifera, the following subdivisions can be distinguished for the Miocene:

1. Lower Miocene–*Globigerinoides trilobus, Globigerinita dissimilis, Globoquadrina altispira, G. dehiscens* and *Globigerinatella insueta.*

2. Lower part of Middle Miocene–*Globorotalia praemenardii, G. fohsi barisanensis, G. fohsi fohsi, G. fohsi lobata, Orbulina suturalis* and *O. bilobata.*

3. Upper part of MIddle Miocene (Tortonian Stage)–*Globorotalia menardii, Orbulina universa, Sphaeroidinellopsis grimsdalei, Globigerina nepenthes* and *Hastigerina siphonifera.*

4. Upper Miocene (Messinian Stage)–*Globigerinoides obliquus, Globigerina nepenthes, Sphaeroidinellopsis seminulina, Globoquadrina altispira* combined with sporadic *Pulleniatina obliquiloculata* (probably *P. primalis*) and *Sphaeroidinella dehiscens.*

Pliocene deposits of the Philippines (Bandy, 1963b; Bandy and Wade, 1967) are characterized by *Pulleniatina obliquiloculata, Sphaeroidinella dehiscens, Globigerina eggeri, Globorotalia puncticulata, G. inflata* and *G. truncatulinoides* (probably *G. tosaensis*).

Taiwan

Distribution of planktonic foraminifera in the Neogene deposits of Taiwan is presented in the papers of L. Chang (1959a, 1959b, 1962a, 1962b, 1964, 1965, 1966, 1967), S. Chang (1965) and Huang (1963), but lithologic peculiarities of the deposits (coal-bearing members, interlayers of coarse sandstone and conglomerate, volcanogenic formations) do not often allow the observation of a continuous succession of planktonic-foraminiferal assemblages.

Rocks with planktonic foraminifera of the lower part of the Lower Miocene (*Globorotalia kugleri* and *Globigerina dissimilis* Zones) are not certainly recognized. The upper part of the lower Miocene (*Globigerinatella insueta* Zone) is characterized by *Globigerinoides trilobus, G. bisphaerica, Globoquadrina altispira, G. dehiscens* and *Praeorbulina* sp. (Kohan and Tairyo Formations, probably basal layers of the Sogo and Peikang Formations of west Taiwan; the lower part of the Hori Formation of central Taiwan; basal layers of the Kosyun Formation on the Hengchun Peninsula).

For the lower part of the Middle Miocene, typical species are: *Orbulina suturalis, O. bilobata, Hastigerina siphonifera, Globorotalia fohsi barisanensis, G. fohsi fohsi* and *G. obesa* (Nanko Formation, the lowermost part of the Shuilin Formation, the upper part of the Sogo and Peikang Formations of West Taiwan, the middle part of the Kosyun Formation on the Hengchun Peninsula).

To the upper part of the Middle Miocene (Tortonian Stage) and the Upper Miocene should be assigned deposits containing *Orbulina universa, Globorotalia menardii, G. scitula, G. miocenica, G. acostaensis, G. mayeri, Globigerinoides obliquus, G. elongatus, Globigerina nepenthes, G. bulloides, G. apertura, Sphaeroidinellopsis seminulina* and *S. subdehiscens* (Sankyo Group and the main part of the Shuilin Formation of west Taiwan, the upper part of the Kosyun Formation on the Hengchun Peninsula). However, it is difficult to draw an exact boundary between the Tortonian and Messinian Stages.

Pliocene deposits on the western and eastern coasts of Taiwan contain *Sphaeroidinella dehiscens, Pulleniatina obliquiloculata, Globorotalia inflata, G. crassaformis, Globigerinoides conglobatus, G. ruber* and *G. sacculifera.*

Japan

Planktonic foraminifera of Paleogene deposits of Japan have been studied by Asano (1958, 1962a, 1962b), Saito (1962), and Asano and Takayanagi (1965).

Paleocene deposits have been recognized on the siland of Hokkaido: Danian Stage–*Globigerina daubjergensis, Globorotalia pseudobulloides, G. compressa, Globigerina* sp. cf. *G. triloculinoides* (Choboshi Formation); and upper Paleocene–*Globorotalia pseudomenardii* (Chippomanai Formation).

To the lower part of Middle Eocene belongs the Kyoragi Formation, which contains *Globorotalia bullbrooki, G. spinuloinflata, G. bonairensis* and *Globigerina boweri* (Amakusa Island).

To the upper part of Middle Eocene (*Orbulinoides beckmanni* Zone) is assigned the Hahajima Limestone, which contains *Orbulinoides beckmanni, Globigerinatheca barri, Hantkenina dumblei, Truncorotaloides topilensis, Globorotalia centralis* and *G. lehneri* (Hahajima Island).

There are no data in the literature on the planktonic foraminifera of the Lower Eocene of Japan; the Upper Eocene and Oligocene contain very poor faunas.

Neogene deposits of Japan are characterized by a rather varied fauna of planktonic foraminifera (Asano, 1962a, 1962b; Asano and Hatai, 1967; Saito, 1960, 1963; Takayanagi and Saito, 1962; Matoba, 1967).

Saito (1963) subdivided the Miocene of Honshu Island into eight biostratigraphic zones:

1. The *Globigerinita unicava* Zone contains *G. unicava, G. dissimilis, G. stainforthi, Globigerinoides*

trilobus, Globoquadrina praedehiscens, Globigerina falconensis, G. angustiumbilicata, G. woodi and *G. venezuelana.* This zone corresponds to the *Globigerinita dissimilis* Zone of the Caroline Ridge (Lower Miocene).

2. The *Globigerinatella insueta* Zone contains *G. insueta, Globoquadrina dehiscens, G. altispira, G. quadraria, Globigerinoides trilobus, G. subquadratus, Globorotalia obesa* and *G. fohsi barisanensis;* such species as *Globigerinoides bisphaerica, Praeorbulina glomerosa* and *P. transitoria* are common for the upper part of the zone. This zone corresponds to the like zone of the Caroline Ridge (Lower Miocene).

3. The *Globorotalia fohsi barisanensis* and *G. fohsi fohsi* Zones have a similar micropaleontological character—with *Orbulina suturalis, Hastigerina siphonifera, Globorotalia praemenardii, G. mayeri* and *G. scitula praescitula*—and belong to the lower part of the Middle Miocene.

4. The *Globorotalia byrovae* Zone is characterized by *G. byrovae, G. mayeri, G. scitula, Orbulina suturalis, O. universa* and *Globoquadrina altispira.* In its uppermost part appear *Globorotalia menardii, G. lenguaensis, G. acostaensis* and *Globigerinoides bollii.* The deposits of this zone seem to belong to the lower part of the Middle Miocene ("Langhian" Stage), with the exception of layers with *Globorotalia menardii.* The latter indicate the Tortonian Stage.

5. The planktonic foraminiferal assemblages of the *Globorotalia mayeri–Globigerina nepenthes* Zone and that of the *Globorotalia menardii–Globigerina nepenthes* Zone are very similar. They include *Globorotalia menardii, G. miocenica, Globigerina decoraperta, G. nepenthes, Globigerinoides obliquus* and *G. elongatus.* Only *Globorotalia mayeri* does not range from the lower zone into the upper one. These two zones are attributed to the Tortonian Stage (Middle Miocene). The *Globorotalia menardii–Globigerina nepenthes* Zone is not accepted as extending through the basal part of the Messinian Stage (Upper Miocene) as well.

6. The Miocene of Honshu ends with the *Sphaeroidinellopsis seminulina* Zone, where *S. seminulina* and *S. subdehiscens* are widely developed. The deposits of this zone belong to the Messinian Stage (Upper Miocene).

Among Pliocene planktonic foraminifera of Japan, common species are: *Sphaeroidinella dehiscens, Pulleniatina obliquiloculata, Candeina nitida, Globorotalia tosaensis, G. inflata, G. crassaformis, Globigerinoides ruber* and *G. sacculifera.*

Kamchatka Peninsula

Thick Paleogene volcanogenic and terrigenous deposits of Kamchatka are characterized by a very poor fauna of planktonic foraminifera, recorded in a limited number of places (Serova, 1967). The following stratigraphic units are distinguished:

1. Lower Paleocene (including the Danian Stage) containing *Globigerina varianta, G. moskvini, G. trivialis, G. triloculinoides, Globorotalia pseudobulloides* and *G.* aff. *compressa* (the *Globigerina varianta* Zone, according to terminology given by Serova).

2. Upper Paleocene (the *Globigerina nana–Acarinina primitiva* Zone) containing *Globigerina nana, G. bacuana, G. coalingensis, Acarinina acarinata* and *A. primitiva.*

3. Lower part of Lower Eocene (the *Globigerina turgida–Acarinina triplex* Zone) containing *Acarinina triplex, Globorotalia aequa, G. whitei, G. stonei, Globigerina turgida, G. nana, G. angipora* and *G. coalingensis.*

4. Upper part of Lower Eocene (the *Globigerina inaequispira–Globigerinella voluta* Zone) containing *Globigerina inaequispira, G. pseudoeocaens* and *Globigerinella voluta* (probably *Pseudohastigerina wilcoxensis).*

5. Lower part of Middle Eocene (the *Globigerina boweri* Zone) containing *Globigerina boweri, G. posttriloculinoides, G. kyushuensis* and *G. yeguaensis.*

California

Investigations carried out by Mallory (1959), Loeblich (1958), Martin (1943), Lipps (1965), and other workers give only a general idea of distribution of planktonic foraminifera in Paleogene deposits of California; a detailed zonal scale is not yet worked out.

The Danian Stage (uppermost part of the Moreno Formation) is characterized by *Globigerina triloculinoides, G. daubjergensis, Globorotalia pseudobulloides* and *G. compressa.* Younger deposits of early Paleocene age (*Acarinina uncinata* and *Globorotalia angulata* Zones) have not as yet been recognized.

To the Upper Paleocene is assigned the lowest part of the Lodo Formation, which contains *Globorotalia pseudomenardii, G. velascoensis, G. acuta* and *G. aequa.*

To the Lower Eocene is assigned the rest of the Lodo Formation, which contains *Globorotalia aragonensis, G. marksi, G. subbotinae* (= *G. rex*), *G. nicoli, Acarinina decepta* and *A. pseudotopilensis.*

The Middle Eocene of California (Cozy Dell and Kreyenhagen Formations) contains *Hantkenina alabamensis, H. dumblei, Globorotalia centralis, Acarinina bullbrooki, A. aspensis, A. pentacamerata, Globigerina boweri, G. bakeri, G. eocaena* and *Globigerapsis* sp.

Upper Eocene deposits containing planktonic foraminifera are not yet known from California.

Deposits of the Zemorrian Stage and those of the lower part of the Saucesian Stage (Lipps, 1965; 1967a, b) are of Oligocene age. A rather rich foraminiferal assemblage consists of *Globigerina ciperoensis, G. officinalis, G. angustiumbilicata, G. ampliapertura, G. senilis, G. sellii, Cassigerinella chipolensis, Globorotalia postcretacea, G. opima nana* and *G. permicra.*

Studies by Lipps (1965; 1967a, b) showed that the Oligocene-Miocene boundary is drawn within the Saucesian Stage. In the upper part of the stage, there appear *Globigerinoides trilobus, Globoquadrina praedehiscens, Globigerinita stainforthi* and *Globorotalia minutissima* (lower part of lower Miocene). The lower Miocene contains deposits of the Relizian Stage with *Globigerinoides trilobus, Globigerinita stainforthi, Globorotalia peripheroronda, G. praescitula, G. obesa* and *Cassigerinella chipolensis.*

The planktonic foraminiferal assemblage of the Luisian Stage (Lipps, 1964) includes *Candorbulina universa, Globigerina concinna, Globoquadrina larmeui, Protentella prolixa, Globorotalia peripheroronda, G. praescitula* and *G. archeomenardii.* This stage should be placed at the base of the middle Miocene. The Mohnian Stage with *Orbulina universa, Globorotalia scitula, G. mayeri, Globigerina bulloides* and *G. quinqueloba* belongs to the late middle Miocene.

The Miocene appears to end in Delmontian Stage deposits with *Sphaeroidinellopsis subdehiscnes, S. seminulina, Globigerina apertura, G. quinqueloba, G. decoraperta* and *Globigerinita glutinata* (upper Miocene).

The Pliocene of California (Venturian Stage) is characterized by *Pulleniatina obliquiloculata, Sphaeroidinella dehiscens, G. tumida, G. inflata, G. crassaformis, Globigerinoides conglobatus* and *G. sacculifera* (Ingle, 1967).

This short review of the stratigraphic subdivision of Tertiary deposits of the northern part of the Pacific province by means of planktonic foraminifera has resulted in several conclusions. In many parts of the province, the authors observe similar assemblages of planktonic foraminifera, as well as the same succession of these assemblages through time. Thus, a unified scale of chronostratigraphic zones may be used for Tertiary deposits of this vast territory. Owing to ecologic and preservational conditions unfavorable for planktonic foraminifera, however, the number of foraminiferal species is in many places considerably impoverished.

Microfauna-rich Paleogene and Neogene pelagic chalk oozes penetrated by drilling on the Caroline Ridge, Shatsky Rise and Horizon Ridge provide ideal conditions for study of the specific composition of planktonic foraminiferal assemblages of the Pacific province and their distribution in the stratigraphic section. Therefore, the results of study of sediment from Leg 6 of the cruise of the *Glomar Challenger* are an important contribution to the stratigraphy of Tertiary deposits of the Pacific Ocean.

Radiolaria

The accompanying chart (Figure 7) records the best known occurrences with regard to radiolarian content and age on the Pacific perimeter. Radiolarians in this region are generally poorly known, although reported finds are fairly widespread. In addition to those recorded on the chart, radiolarians are known from Kamchatka (Mesozoic), the Philippines (Mesozoic), Guam (Eocene), various East Indian islands of which Roti is an example (Mesozoic and Tertiary), and Australia and New Zealand (Mesozoic and Tertiary). In South America, reported occurrences include those in Ecuador (Cretaceous, Eocene, Oligocene and Miocene), Peru (Miocene) and Chile (Tertiary ?). In North America occurrences outside California include those in Oregon (Mesozoic and Tertiary) and Alaska (Mesozoic and Tertiary).

SEDIMENTATION RATES

A recent compilation by Berggren (1969) of radiometric and paleomagnetic ages as related to Cenozoic planktonic foraminiferal ranges provides a reasonable basis from which the duration of microfossil zones can be estimated. Approximate sedimentation rates calculated for cores from Leg 6 incorporate the range of interpretations of the duration of zones within the context of the Berggren scale based, respectively, on foraminifera, calcareous nannoplankton and radiolarians. In a certain section of upper Oligocene sediment at Site 55 (latitude 09° 18.1'N, longitude 142° 32.9'E), for instance, the time of accumulation was variously estimated as 1 to 5 million years, depending on which fossil group was being considered. The resulting ranges of sedimentation rates, thus determined, are given in Figure 8.

The best approximations of sedimentation rate are made in continuously cored sections. Where only discontinuous cores were taken through the sediment section, only average rates between core intervals or the surface can be calculated. These average figures may mask unconformities and abrupt changes in rate of deposition.

Highest sedimentation rates are noted for middle Miocene volcanic-ash deposits in the Philippine Basin and at the western margin of the Mariana Trench—up to 100 meters per million years. Other moderately high rates are indicated for the Upper Oligocene carbonate-siliceous ooze of the Caroline Ridge (4 to 37? meters per million years), the Upper Pliocene and Quaternary

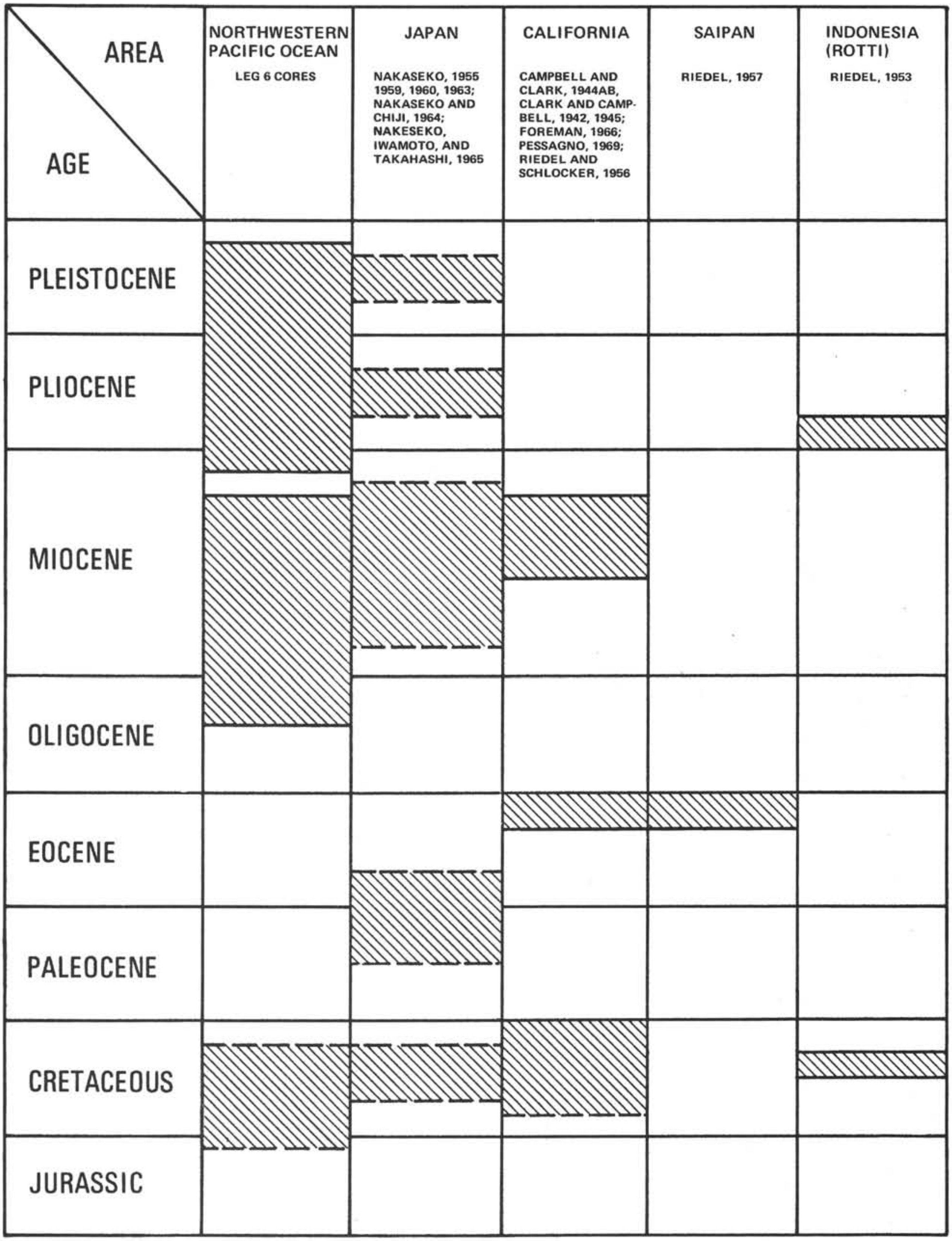

Figure 7. *Occurrence of known radiolarian-bearing strata in land sections of the Pacific region compared to distribution of radiolarian-bearing strata in cores from the northwest Pacific Ocean.*

AREA	HORIZON RIDGE	ABYSSAL PLAIN	SHATSKY RISE			ABYSSAL PLAIN		PHILIPPINE BASIN		CAROLINE RIDGE			ABYSSAL PLAIN	TRENCH MARGIN
AGE / SITE	44	45	47	48	50	51	52	53	54	55	56	57	59	60
QUATERNARY			13-15	8?	12?	16?	1?	2?	6?	8-25		11?	5?	5?
LATE PLIOCENE			12-13			25?				6-8				
EARLY PLIOCENE										–				
LATE MIOCENE						0.02?				3-5	4-7			
MIDDLE MIOCENE								11?	100	4	3-12			37?
EARLY MIOCENE										4-5	–			
LATE OLIGOCENE										4-23	9-30	37?	1?	
MIDDLE OLIGOCENE		4?												
EARLY OLIGOCENE	1-2													
LATE EOCENE	1-2													
MIDDLE EOCENE	4-8	1?												
EARLY EOCENE			3											
LATE PALEOCENE			2-4											
EARLY PALEOCENE														
MAESTRICHTIAN			7-10	9										
TURONIAN and SENONIAN														
CENOMANIAN														

Figure 8. *Geologic ages of rock intervals sampled at drilling sites in the northwest Pacific are shown with approximate sedimentation rates based on microfossil evidence given in bubnoffs (meters per million years). Rates averaged over intervals where cores are widely spaced are queried.*

carbonate-siliceous ooze of the Shatsky Rise and Caroline Ridge (6 to 25 meters per million years), and, Maestrichtian carbonate ooze of the Shatsky Rise (7 to 10 meters per million years).

Coring of abyssal sediment was discontinuous, and only average rates between coring runs are available. Low rates averaging 1 to 5 meters per million years are indicated for most abyssal areas cored during Leg 6. An exception that provides insight into possible deficiencies of the average rates is noted for the abyssal section cored at Site 51 (latitude 33° 28.5′N, longitude 153° 24.3′E). An Upper Cretaceous (Santonian) carbonate ooze there was recovered at 125 meters. The sediment above is noncalcareous zeolitic clay with volcanic sand, some chert, diatoms and radiolarians, but no calcareous microfossils. Siliceous microfossils from subbottom depths of 23 to 32 meters are late Pliocene and early Quaternary in age. Those from 114 to 123 meters are late Miocene to early Pliocene. An average sedimentation rate based on the Cretaceous calcareous microfossils alone is 1 meter per million years, but the Miocene and Pliocene sediment directly above is separated from the Cretaceous by a major unconformity. The average rates calculated above are 25 meters per million years for the Pliocene and 16 meters per million years for the Quaternary. The common occurrence of volcanic material in these younger beds accounts for the unusually high late Cenozoic abyssal sedimentation rate, and, if the calcareous microfossils of the Cretaceous had been all that were available at Site 51, an erroneous average sedimentation rate for the whole section might have been reported.

RELATIONSHIP TO ACOUSTOSTRATIGRAPHY

Sonic reflections from horizons in rock strata below the ocean floor provide an indirect way of interpreting oceanic stratigraphy and correlating over wide regions at least the rock properties responsible for the sonic character of the strata. Reflector horizons are abrupt changes in the nature of the strata that provide interfaces from which sound waves transmitted from the ship are reflected and then recorded again aboard the ship. In many instances, differences in the degree of induration, such as, consolidated volcanic ash beds in a sequence of unconsolidated volcanic ash, or contrasting rock types (limestone, basalt, chert), produce the reflectors and represent changes in the strata that may in part be time-transgressive and even strata-transgressive. For example, during Leg 6, cores were obtained from the "upper opaque layer" (shallowest layer with many internal reflectors) which showed the age of this layer in various parts of the region to range from Oligocene to Late Cretaceous (Figure 9).

Through the use of a continuous seismic profiler, the acoustic properties below the sea floor have been obtained along the traverse of the *Glomar Challenger* in the northwestern Pacific. The major divisions of the sediment cover in this area of the Pacific based on acoustic properties have been recognized and interpreted by Ewing and others (1968). They identified five seismic layers: an upper transparent layer, which contains no significant internal reflectors and is less than 100 meters thick over much of the north Pacific; an upper opaque layer, whose opacity (number and spacing of internal reflectors) varies regionally and which seems to be absent in the eastern Pacific; a generally quite thin lower transparent layer that is relatively independent of topography; a lower opaque layer, Horizon B, which, where it is present, is underlain by no deeper reflectors; and, the "acoustic basement," which is characterized as having a rough surface.

Despite regional variations in the acoustic layers and the fact that the lower layers cannot everywhere be distinguished, acoustostratigraphy provides an important tool in exploration of the sea floor, at least locally. Of concern here is the age relationship of the acoustic layers in different parts of the Leg 6 area and their correlation.

Microfossil evidence from cores penetrating the acoustic layers indicates that the layers are not consistent ocean-wide time horizons. The top of the upper opaque layer is one of the most distinct reflectors at any given place in the Pacific. The ages of the horizon based on calcareous nannoplankton, foraminifera, and radiolarians from beds that correspond to, or are in close proximity to, the beds responsible for the acoustic properties illustrates the general age relationships (Figure 9). On Horizon Ridge (Site 44), the first reflector is identified as Eocene chert; in the abyssal plain of the Pacific (Site 45), it is Eocene lithified volcanic ash; on the Shatsky Rise (Sites 47, 48), it is Upper Cretaceous chert; and, in the Philippine Basin, it is Miocene volcanic ash. Thus, the sediment cover above the upper opaque layer within the northwestern Pacific in places may be exclusively late Tertiary or may be Late Cretaceous through Tertiary. There also appears to be no systematic regional variation in the age of the reflector. In the eastern part of the Leg 6 area it is middle Eocene, whereas, in the central part it ranges from Eocene to Cretaceous. Across the trench system in the Philippine Basin, the reflector is dated once again as Tertiary—here a Miocene volcanic ash. Farther to the south, the acoustic records are different than in the northern Pacific and Philippine Basins. On the Caroline Ridge, beneath an upper transparent layer, a single smooth strong internally reflective layer is identified. If this layer is interpreted as the upper opaque layer, rather than as Horizon B, then the layer corresponds to basalt overlain by Miocene chalk ooze (Sites 55, 56 and 57).

Several attempts were made to date the lower transparent layer and Horizon B, but some were unsuccessful because of impenetrable chert of silicified beds above.

REFLECTOR	HORIZON RIDGE	ABYSSAL BASIN		SHATSKY RISE	ABYSSAL BASIN		PHILIPPINE BASIN	CAROLINE RIDGE
	Site 44	Site 45	Site 46	Sites 47-50	Sites 51 and 59	Site 52	Sites 53-54, 60	Sites 55-58
UPPER TRANSPARENT LAYER	TERTIARY CHALK OOZE	TERTIARY BROWN CLAY	OLIGOCENE AND EOCENE; PARTLY LITHIFIED ASH AND ZEOLITIC BROWN CLAY.	TERTIARY AND LATE CRETACEOUS CHALK OOZE	TERTIARY ZEOLITIC BROWN CLAY	TERTIARY AND CRETACEOUS VOLCANIC-ASH-RICH BROWN CLAY	LATE TERTIARY VOLCANIC ASH AND BROWN CLAY	LATE TERTIARY CHALK OOZE
UPPER OPAQUE LAYER	EOCENE CHERT	OLIGOCENE AND EOCENE VOLCANIC ASH, PARTLY LITHIFIED LATE CRETACEOUS CHALK (CENOMANIAN)		LATE CRETACEOUS (MAESTRICHTIAN) CHERT	CRETACEOUS CHERT AND RADIOLARIAN–RICH BROWN CLAY		MIOCENE VOLCANIC ASH	
LOWER TRANSPARENT LAYER			CRETACEOUS RADIOLARIAN CHERT AND BROWN CLAY	EARLY CRETACEOUS AND LATE JURASSIC CHALK OOZE			MIOCENE OR OLIGOCENE CHALK (SITE 53 ONLY)	
BASEMENT OR "B"				LATE JURASSIC OR OLDER BASALT AND RED CHERT			PRE-MIOCENE BASALT	EARLY TERTIARY BASALT

Figure 9. *Age and lithology of sonic reflectors at drilling sites in the northwest Pacific Ocean. (Reflector names after Ewing and others, 1968.)*

The lower transparent layer was encountered, however, as a chalk or chalk ooze facies of Oligocene or Miocene age in the Philippine Basin, of Late Jurassic or Early Cretaceous age at the Shatsky Rise, and of Late Cretaceous age in the abyssal Pacific area.

Horizon B appears to have been reached at the bottom of Hole 50.0. Fragments of red chert and altered volcanic rock were recovered with lowermost Cretaceous microfossils at a depth in the hole which approximately corresponded to Horizon B on the profiler record. Whether the horizon was reached or not, the cores indicate a minimum age for the reflector at this locality of latest Jurassic. This age agrees with the earlier prediction of the age of Horizon B on Shatsky Rise by Ewing and others (1968) based chiefly upon rates of accumulation.

On Shatsky Rise, two acoustic reflectors are identified that cannot be traced into the abyssal sediment adjacent to the Rise (Ewing and others, 1966). One occurs within the upper transparent layer, at fairly shallow depth (approximately 100 meters), and is called "alpha"; the second, "beta," occurs near the bottom of the upper opaque layer. Both reflectors show prominently on the profiler records of the site-surveying ship *Argo* and the drilling ship *Glomar Challenger.* The alpha reflector was drilled at Sites 47 and 48, but beta was not reached. At Sites 47 and 48, alpha corresponds to an unconformity at the base of the upper Miocene. The Miocene rests on Eocene chalk ooze in Hole 47.2, and the Oligocene and part of the Eocene are truncated. To the east at Site 48, the hiatus is greater, and the Miocene is in contact with Upper Cretaceous chalk.

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APPENDIX
TAXONOMIC RECOMBINATIONS OF CALCAREOUS NANNOPLANKTON

Chiasmolithus expansus (Bramlette and Sullivan)
basionym:
Coccolithus expansus Bramlette and Sullivan, 1961, *Micropaleontology.* 7 (2), p. 139, pl. 1, figs. 5a-5d.

Coccolithus subdistichus (Roth and Hay)
basionym:
Ellipsolithus subdistichus Roth and Hay, 1967, *Trans. Gulf Coast Assoc. Geol. Soc.* 17, p. 446, pl. 6, fig. 7.

Discolithina ocellata (Bramlette and Sullivan)
basionym:
Discolithus ocellatus Bramlette and Sullivan, 1961, *Micropaleontology.* 7 (2), p. 142, pl. 3, figs. 2a-2c.

Helicopontosphaera lophota (Bramlette and Sullivan)
basionym:
Helicosphaera seminulum lophota Bramlette and Sullivan, 1961, *Micropaleontology.* 7 (2), p. 144, pl. 4, figs. 3a-3b, 4.

Helicopontosphaera reticulata (Bramlette and Wilcoxon)
basionym:
Helicosphaera reticulata Bramlette and Wilcoxon, 1967, *Tulane Stud. Geol.* 5 (3), p. 106, pl. 6, fig. 15.