# 36. BIOSTRATIGRAPHY OF THE EQUATORIAL EAST PACIFIC RISE[1]

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## INTRODUCTION

Leg 16 completed the Deep Sea Drilling Project coring program in the eastern equatorial Pacific, which also includes coring done during Legs 5, 8, and 9. Data and materials obtained permit evaluation of regional biostratigraphic correlation, fossil preservation, and paleontologic evidence for large-scale tectonic movement. Many of the most significant sites are continuously cored and reach basalt (Figure 1). Comparison of the relative position of zonal boundaries for the three major microfossil groups – foraminifers, coccoliths, and radiolarians – reveals some differences from hole to hole. Such offset relations are usually within the limits of a single zone for a given DSDP leg. Some of the variation results from a contrasting preservation state of fossil groups related to their particular depth of deposition on the west flank of the East Pacific Rise. Leg 16 sites, cored on a west-trending transect at 10°N, are arrayed down the flank at water depths ranging from 4484 meters at DSDP 159 to 5320 meters at DSDP 163.

Although Late Cretaceous and Eocene to Pleistocene sediments are identified at the sites of Leg 16, no calcareous microfossils younger than middle Miocene were found, owing to calcite dissolution. Older calcareous assemblages also show the effects of solution, as foraminifers are only sporadically present. Etched coccolith assemblages are common, and only radiolarian assemblages are generally well preserved and present throughout almost all of the cored section. Previously recognized low-latitude zonations are applicable at all the sites, although modification of some parts of the Paleogene radiolarian and coccolith zonations is indicated (Dinkelman, this volume; Bukry, this volume).

The age of fossil assemblages in Oligocene and older sediment directly above basalt is considerably younger than the prescribed age estimated from the associated magnetic anomalies. This difference in indicated age is greater at older sites. But the age of the basal sediment and the depth to basement below the sea floor do show a general increase away from the rise crest. The axes of thickest pelagic sediment for each geologic series indicate a northward post-depositional offset of older equatorial centers of deposition. The apparent northward translation was only about 0.1°/m.y. during the Neogene; it was about 0.5°/m.y. during the Eocene-Oligocene.

## ZONE AND SERIES BOUNDARIES

Late Cretaceous microfossil assemblages are present at Site DSDP 163 at the western margin of the East Pacific Rise. This is the first known occurrence of Mesozoic assemblages from the ocean floor east of the Line Islands and the Hawaiian Islands. A 114-meter section of Campanian and early Maestrichtian calcareous ooze is zoned and correlated primarily by coccoliths, the major sediment component. Small numbers of benthonic foraminifers, planktonic foraminifers, and radiolarians occurring through the section also indicate the Late Cretaceous. The coccolith zonal sequence is similar to that previously observed at other DSDP sites, but no late Maestrichtian assemblages are present, and an abbreviated *Lithraphidites quadratus* Zone is overlain by barren zeolitic clay. The Campanian-Maestrichtian boundary occurs within the *Tetralithus trifidus* Zone, as indicated by more abundant planktonic foraminifers in other areas, as at Atlantic Sites DSDP 10 and DSDP 21. Owing to a lack of well-preserved radiolarian and foraminiferal assemblages and because the upper Maestrichtian is nonfossiliferous or uncored, no comparisons of the microfossils at the top of the stage, and thus at the top of the Upper Cretaceous Series, are possible.

Paleocene microfossils are not present in samples from Leg 16. The earliest Cenozoic assemblages recovered (DSDP 162, Core 17) are late early Eocene. Zonal relations for this and other Cenozoic assemblages are summarized in Figure 2. Where feasible, planktonic foraminifers were used to define series and subseries boundaries. Although all three fossil groups – foraminifers, coccoliths, and radiolarians – permit zonation of late early Eocene sediment, the subsequent early middle Eocene is represented in a strongly dissolved facies, where only radiolarian assemblages can be zoned with assurance. The lower Eocene-middle Eocene subseries boundary is based partly on the *Discoasteroides kuepperi* Zone of coccoliths, which has previously been correlated with the lower *Hantkenina aragonensis* Zone of foraminifers in DSDP 94, Sections 26-3 to 28-3 (Worzel, Bryant et al., in preparation). At DSDP 162 the foraminiferal assemblage is considered to be transitional between the *Globorotalia palmerae* Zone and the *H. aragonensis* Zone.

The middle Eocene-upper Eocene boundary, as determined by radiolarian assemblages, lies near the upper boundary of the *Podocyrtis chalara* Zone and the lower boundary of the *Podocyrtis goetheana* Zone. At DSDP 161A and DSDP 162 this boundary can be clearly identified. But because of intense vertical mixing within the cores at DSDP 163, the presence of this boundary can only be inferred from the relative abundance of a sphaeroid

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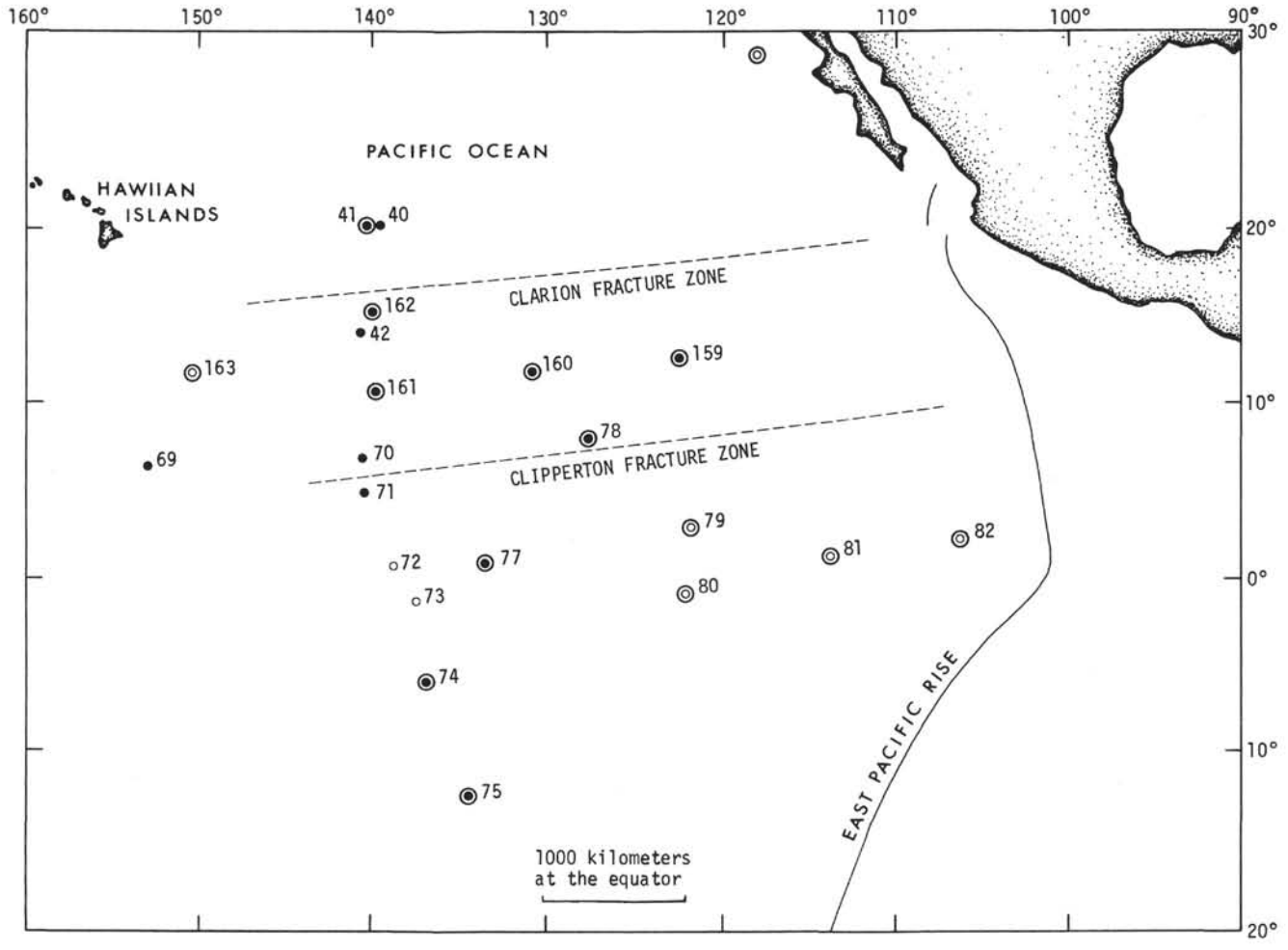


Figure 1. *Location of DSDP coring sites and the Experimental Mohole (EM) on the west flank of the East Pacific Rise. Holes continuously cored shown as solid circles; those that terminate in basalt as double circles. Sites from DSDP 159 to DSDP 163 were cored during Leg 16.*

radiolarian, probably *Periphaena decora*, in samples from both zones, as this species is dominant in samples from the same interval at DSDP 161A and DSDP 163 (Plates 1 and 2).

Riedel and Sanfilippo (1970) divided the upper Eocene into two zones based on radiolarians, the *Thyrsocyrtis tetracantha* Zone and the *Thyrsocyrtis bromia* Zone, plus an unzoned interval at the base of the upper Eocene. This interval was later placed by Moore (1971) into the *Podocyrtis goetheana* Zone. The *Thyrsocyrtis tetracantha* Zone was not observed at any of the three Leg 16 sites which cored Eocene sediments. At every site *Thyrsocyrtis bromia* appeared before the first occurrence of *Thyrsocyrtis tetracantha*. Examination of the data presented in the radiolarian reports of Legs 4, 7, and 8 (Riedel and Sanfilippo, 1970, 1971; Moore, 1971) does not substantiate the presence of the *T. tetracantha* Zone in either the Caribbean or the Pacific. Thus it seems appropriate to eliminate the use of the *T. tetracantha* Zone in future radiolarian work. Hence, the upper Eocene is divided into two zones, the *P. goetheana* Zone and the *T. bromia* Zone. It may even be advisable to omit the *Thyrsocyrtis bromia* Zone as well, considering the wide morphological variety of the nominate species, as discussed and illustrated in Dinkelman (this volume), and to consider other upper Eocene species, like *Lophocyrtis*(?) *jacchia* (Ehrenberg) and *Cyclampterium*(?) *milowi* Riedel and Sanfilippo, to establish a new upper Eocene zonation.

The Eocene-Oligocene series boundary is identified in DSDP 161A and DSDP 162 at a distinct lithologic change from radiolarian-rich brown clay below to grayish orange coccolith-radiolarian ooze above. Among radiolarians, a discontinuity occurs in the morphologic lineage of *Theocyrtis tuberosa* at both sites. The basal Oligocene coccolith subzone is missing, and the late Eocene is so decimated by solution of calcareous material that part of that interval also may be missing. At DSDP 161A the Eocene-Oligocene boundary is drawn at the same level, between the *Discoaster barbadiensis* Zone and *Helicopontosphaera reticulata* Zone of coccoliths and between the *Thyrsocyrtis bromia* Zone and *Theocyrtis tuberosa* Zone of radiolarians; foraminifers are absent or nondiagnostic. This coincidence of boundaries is at a lithologic discontinuity between Cores 9 and 10. At DSDP 162 the top of the *D. barbadiensis* Zone and *T. bromia* Zone are offset so that the upper part of the *T. bromia* Zone of radiolarians is associated with the *H. reticulata* Zone of coccoliths. Again, samples are barren or nondiagnostic on the basis of foraminifers.

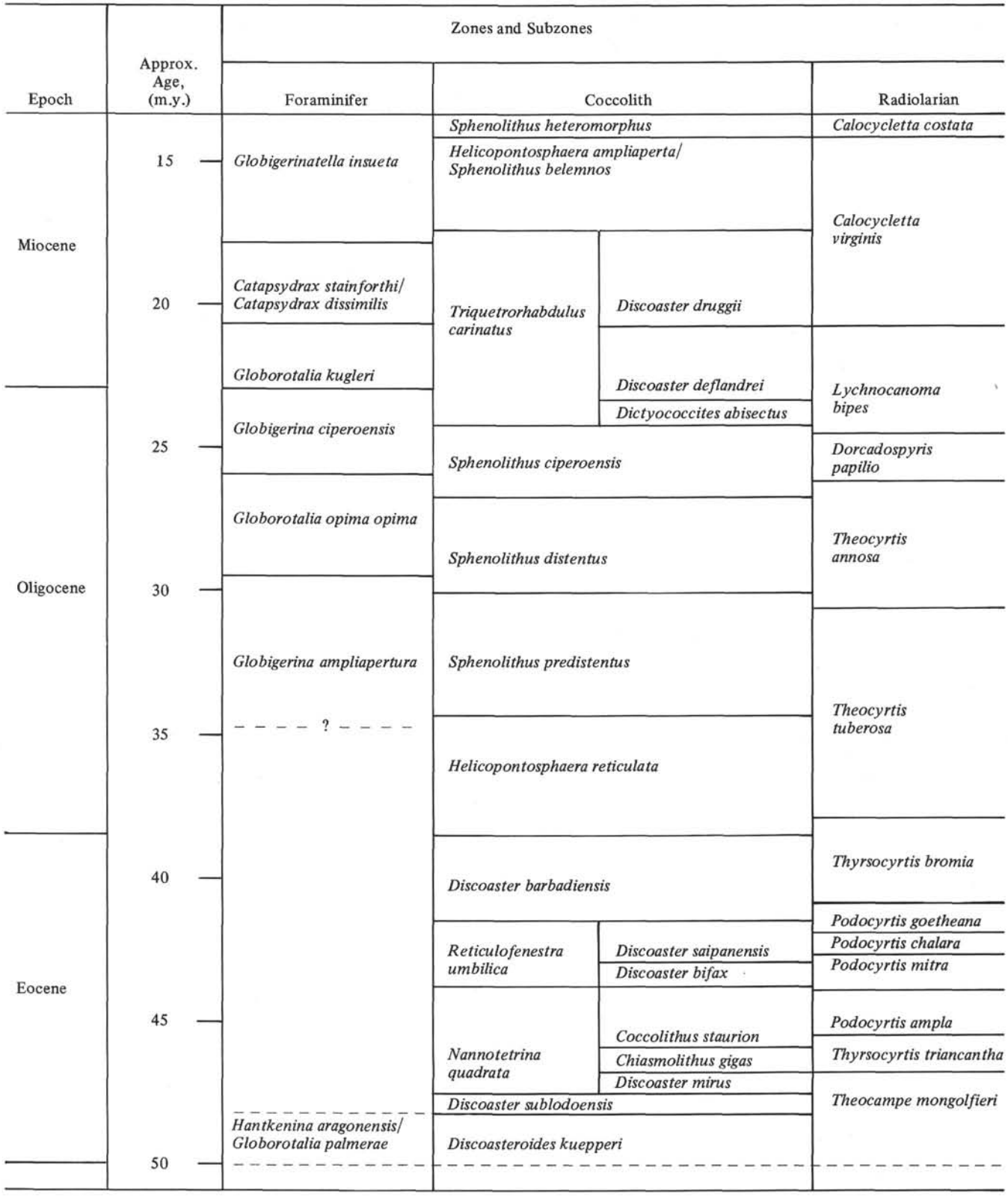


Figure 2. *Summary of Cenozoic zonal relations observed in DSDP Leg 16 cores from the west flank of the East Pacific Rise.*

Variations in the offset relations of foraminiferal-coccolith-radiolarian zone boundaries occur even within a single Deep Sea Drilling Project leg, where several significant variables in zone identification can be held reasonably constant (Bukry et al., 1971; Tracey et al., 1971). For example, on any given leg the same micropaleontologists determine the biostratigraphy for all the sites, the sites are generally limited to one or two regions having similarities in sedimentation and paleoecology, and samples taken for study can be clustered at the same level in the core for all

three microfossil groups. Minor inconsistency in zonal relations would be mainly the result of variation and identification of preservation and reworking, if ideal continuous core recovery were assumed. Undetected voids in core recovery (Moore, 1972), however, could also alter the observed relations of zone boundaries. Further discrepancies are introduced in comparing zonations between regions, based on samples examined by different workers having differing species and zonal concepts. Fluctuations in intergroup biostratigraphic correlations showing boundary offsets of one or two zones seem inevitable. Zonal boundaries based on the last occurrence of a single species, though often utilized, probably contribute a continual source of variation. Compare the zonal summaries shown in Figure 2 with those of Berggren (1972) and Tracey et al. (1971). Simple comparison of species ranges instead of "zones" might reduce one source of bias. Statistical averaging of relative ranges and lineage analysis might also prove useful. But operator variation in identifying taxa and preservation states will provide a continuing source of aberration.

The lower Oligocene-upper Oligocene boundary has been designated at the top of the *Globigerina ampliapertura* Zone of foraminifers and closely approximates but is slightly higher than the tops of the *Sphenolithus predistentus* Zone of coccoliths and the *Theocyrtis tuberosa* Zone of radiolarians at DSDP 160 and DSDP 161. At both sites the tops of the three zones show the same relative positions: *G. ampliapertura* Zone highest, *T. tuberosa* Zone lowest. The relation between these zone boundaries is typically less consistent in other Pacific areas (compare DSDP Legs 7 through 9).

The Oligocene-Miocene boundary was sampled at Sites DSDP 159 through DSDP 161. Only two of the three microfossil groups can be zoned at the boundary for these sites. At DSDP 159 the base of the *Globorotalia kugleri* Zone of foraminifers is used to identify the boundary. This level corresponds with the middle of the *Triquetrorhabdulus carinatus* Zone of coccoliths, designated the *Discoaster deflandrei* Subzone. No radiolarian assemblage is present. At the other two downslope sites, the *G. kugleri* Zone is not recognized, owing to solution of foraminifers. At both of these sites the top of the *D. deflandrei* Subzone coincides with the top of the *Lychnocanoma bipes* Zone of radiolarians. At DSDP 160 the highest *Globigerina ciperoensis* Zone assemblage of foraminifers occurs within the intervals of the *D. deflandrei* Subzone and *L. bipes* Zone, indicating again that at least the lower parts of these two zones should be assigned to the Oligocene in this region. Similar relations have been indicated in previous studies of cores from the Pacific (DSDP Legs 6 through 9).

As calcareous microfossils are rare or absent in higher series and subseries, no zonal comparisons at boundaries are possible. All post-middle Miocene correlations are based on radiolarian zonation.

## PALEOECOLOGY

Microfossil zonations previously established for low-latitude assemblages have been applicable at all DSDP Leg 16 sites. Warm-water assemblages of radiolarians and coccoliths are most representative, because solution has severely limited the occurrence of foraminifers and diatoms. Where they do occur, these groups too are represented by low-latitude taxa such as *Asterolampra, Asteromphalus,* and *Globigerina ciperoensis*. Deposition in a low-latitude, open-ocean environment is indicated for all Late Cretaceous to Pleistocene assemblages from DSDP Leg 16.

## PRESERVATION

### Definitions

The term preservation, as applied to fossil skeletons, is used to help describe the present physical condition of fossils relative to their presumed pristine state. Recognition of various states of preservation, therefore, requires a concept of a pristine species as a point of reference from which to gauge alteration of a fossil structure. Because all fossil skeletons have undergone some degree of alteration from the pristine state and because the experience and insight of observers in determining species concepts differs, recognition of variation in preservation states is partly subjective.

Pristine skeletal structures may be altered by mechanical or chemical processes. Mechanical processes are consistently destructional, whereas chemical processes may be either destructional or constructional. A skeletal compound in a sedimentary environment that has pore fluid supersaturated with the same compound can acquire a secondary coating altering its original morphology. Conversely, in an undersaturated environment, part of the skeleton can go into solution. Significant taxonomic consequences result from both varieties of alteration, because a feedback relation in recognition can exist between skeletal preservation and skeletal taxonomy. Taxonomy, the art of classifying, describing, and naming species, is based, in the case of fossils, on variation in skeletal structures. These same structures can be secondarily altered by solution or overgrowth, and more significantly the alteration can be selective for certain structures on the same skeleton. Some structures may be severely modified whereas others may remain essentially unaltered. In general practice, the least altered, central reference form of a species can be determined by comparing coeval assemblages having different types of preservation. The sequential relation of preservation states also can sometimes be observed in thick sections of sediment, where the states differ from top to bottom.

The general sequence of processes leading to the preservation state (final form) of planktonic microfossils can be considered under five partly overlapping chronologic categories: production, predation, solution, accumulation, and diagenesis.

### Production

Production of skeletal material by planktonic organisms initiates the sequence of steps leading eventually to recognition of variation in fossil form. Processes affecting the living organism itself can alter the initial form of a skeleton from the central species concept. For example, ecophenotypic responses by the organism to environmental conditions may be reflected in its skeleton. The Quaternary coccolithophore *Emiliania huxleyi* produces a more compact skeletal shield composed of fewer structural elements

when subjected to cooler temperature (Watabe and Wilbur, 1966; McIntyre and Bé, 1967).

Typical skeletons of a species are constructed of elements or in shapes that have variable thickness and crystallographic character in certain parts of the skeleton. Therefore, the potential alteration of form by later differential solution or overgrowth is inherent in all but the simplest microfossils (Caulet, 1972). Such alteration affects species identification and recognition of preservation states.

### Predation

Predation by other organisms subjects skeletal structures to organic degradation through mechanical and chemical digestive processes. But a benefit, from the standpoint of good preservation, may be obtained through predation that results in skeleton-bearing fecal pellets (Schrader, 1971). Aggregations of microscopic skeletons at the centers of the pellets can be protected from external nonorganic chemical solution during passage downward through progressively more undersaturated ocean water to the bottom. Also, because the mass of such pellets is far greater than that of the small individual skeletons, their more rapid sinking through the water affords additional protection.

### Solution

Nonorganic solution of skeletons, as they settle from the upper ocean layer to the bottom, is dependent on mineralogy. Dissolving of calcareous skeletons increases downward because of the progressively greater calcite undersaturation at depth (Peterson, 1966). Siliceous skeletons are subject to more solution in the upper ocean layers than at depth because those layers are typically less saturated with silica than at depth (Berger, 1968a). Oceanic currents and upwelling may extend the length of time the skeletons are exposed to solution conditions and may locally alter the general level of undersaturation.

### Accumulation

Accumulation of skeletons in the upper layer of sediment at the ocean bottom involves a complex of processes which can have great effect on the final preservational form of microfossils. Significant organic and nonorganic processes operate simultaneously. Organic processes involve the activities of benthic invertebrates such as echinoderms and worms, which ingest sediment at and just below the surface. This may subject skeletons to renewed digestive degradation. It may also physically recycle microfossils from the relative protection of shallow burial back to the hostile sediment surface. There, they may be resubjected to nonorganic chemical disequilibria and to further organic degradation. Bacterial activity in the sediment may also create chemical disequilibria that affect solution and overgrowth potential. Nonorganic factors affecting the water-sediment interface are time dependent. Ocean-bottom currents flowing at a rapid rate can delay burial by keeping smaller microfossils in suspension and winnowing them from high areas. The longer a disequilibrium condition is maintained for a given skeleton, the greater will be its destruction through solution. A slow rate of sediment accumulation can produce the same effect in the absence of bottom currents. The length of residence time of a skeleton at the water-sediment interface is critical to its state of preservation, and the degree of disequilibrium is related to ocean depth. Once permanently buried in the sediment, chemical equilibria can be established.

### Diagenesis

Diagenesis encompasses those alterations of form and composition that occur subsequent to final deposition. While still near the surface, where chemical equilibria are being established, both solution and overgrowth can occur together, even among species of the same mineralogy. In carbonate ooze, for example, calcitic discoasters acquire blocky, crystal-faced overgrowths that mask the original skeletal form, whereas calcitic placoliths from the same horizon can be strongly etched, presumably because of differences in crystallite size and orientation.

Opaline siliceous microfossils, which are composed of microcrystalline cristobalite, show no sign of overgrowth. Solution of opaline skeletons, as burial and compaction proceeds, is evidenced by deep-ocean chert layers (Heath, this volume), which commonly contain faint, ghost-like forms of siliceous and calcareous microfossils. Chert is chiefly composed of quartz, a much more stable and less soluble form of silica than the original opaline cristobalitic skeletons. Although all of the factors involved in this diagenetic change are not known, the youngest oceanic chert horizons in the Pacific are Miocene. These youngest cherts are present only where about 300 meters or more of overlying sediment is present. Older cherts are known at shallower levels, but overlying sediment has been eroded away in such cases. Apparently, compaction, as well as length of burial and composition of pore fluids, is a factor in the solution of siliceous microfossils that produces chert in oceanic sediment.

Long-term diagenesis as a result of compaction observed for calcareous microfossils includes flattening of foraminifers and solution-welding of coccoliths, eventually producing limestone. But lithification and overgrowth in fossiliferous carbonate sediment can also occur near the sea floor (Fischer and Garrison, 1967). Submarine diagenesis provides many yet to be determined mechanisms to alter preservation states.

### Resultant Assemblages

Potential sources of alteration of skeletal form and of mixing of such forms are multiple. It is not uncommon in a single sample to find oceanic microfossil assemblages composed of specimens in different states of preservation. Even members of the same species show a range of preservation states depending on the duration and degree of alteration to which individuals were subjected before final deposition. Different preservation potential between species and between genera is a constant element that can be used to estimate paleo-oceanologic conditions (Berger, 1968b; McIntyre and McIntyre, 1971; Bukry et al., 1971). For example, late Eocene microfossil assemblages from East Pacific Rise sites of DSDP Leg 16 contain common well-preserved radiolarians, have only rare, etched coccoliths of the most resistant species, and are barren of foraminifers. This rarity of late Eocene calcareous fossils, in

contrast with a great abundance in the early Oligocene, indicates a large inflection in the curve of the calcium-carbonate cycle, which is believed to have resulted from a shift in productivity rather than from a shoaling of the East Pacific Rise. Actual bottom depths seem to have changed little, because calcareous foraminifers are also rare and strongly dissolved in early Oligocene sediment. This great change in sediment composition resulted from a new dominance in calcareous nannoplankton productivity which forced the calcite composition depth much deeper during the Oligocene (Heath, 1969).

The main contrast between the potential preservation of calcareous and siliceous microfossils lies in the geochemical factors within the sediment that permit calcite overgrowths on coccoliths and foraminifers. Siliceous microfossils can be altered only subtractively because of the very high solubility of opal in oceanic sediment pore water. This difference is reflected in present systems for classifying microfossil preservation states (Figure 3). No categories are required for radiolarian overgrowth. Overgrowth categories are not yet established for foraminifers, because recognition of overgrowth is difficult at their scale. But owing to the smaller size of coccoliths they are routinely examined at high magnifications of 500-20,000 X, whereas foraminifers are examined mainly at 10-100 X. Crystallites are smaller in coccoliths, allowing easier recognition of equivalent overgrowth layers.

As the precision of identification of various preservation states has been improved, and as the preservation states of specimens for each major fossil group in single samples have been determined, a relative sequence between the fossil groups could be defined. The scales of dissolution described a staggered, rather than parallel sequence. In East Pacific Rise assemblages, the extreme dissolution categories for foraminifers – mesolytic and hololytic – coincide with slight to moderate coccolith dissolution stages -2 and -3, and with radiolarian category good. The sequential solution susceptibility of the groups indicates that foraminifers are most rapidly dissolved and radiolarians least rapidly. The occurrence of microfossil groups at DSDP Leg 16 sites from the East Pacific Rise confirms a distribution indicated at rise sites from previous legs (Figure 4). Siliceous silicoflagellates and diatoms are more readily dissolved than the radiolarians; but calcareous coccoliths are less readily dissolved than the foraminifers. Examples of the preservation stages of discoasters and radiolarians from East Pacific Rise samples are illustrated in Plates 3 and 4.

### Preservation at DSDP Leg 16 Sites

Foraminifers, coccoliths, and radiolarians of Cretaceous age are present only at Site DSDP 163 (Cores 15-27). All three groups have been affected by strong solution and are represented by poorly diversified assemblages. Among foraminifers, specimens of the genera *Globotruncana* and *Rugoglobigerina* are rare, suggesting deposition at or below the lysocline. Most foraminiferal assemblages represent the mesolytic dissolution facies of Hsü and Andrews (1970). Preservation of radiolarians from DSDP 163 is characterized as poor. Intensive solution has removed taxonomically significant structures from most radiolarian specimens so that identification is possible only to the genus or family level. Solution has also attacked many structural features of coccoliths. Central-area stem structures are missing from most specimens, and broken rims are common. Although coccolith fragments are generally abundant, only a few resistant species are consistently identifiable. The basal chalk, above extrusive basalt, contains mainly coccolith rim fragments; the identifiable assemblage is dominated by three highly resistant species – *Micula decussata, Watznaueria barnesae,* and *Cretarhabdus crenulatus* without stems. Preservation stages range from -2.0 to -3.5.

| | Foraminifers | Coccoliths | | Radiolarians |
|---|---|---|---|---|
| | Hsu & Andrews 1970 | Roth & Thierstein 1972 | Bukry (this vol.) | Dinkelman (this vol.) |
| Maximum–Minimum–Maximum Overgrowth | | | +5 | |
| | | 0-3 | +4 | |
| | | 0-2 | +3 | |
| | | 0-1 | +2 | |
| | | | +1 | |
| Maximum–Minimum–Maximum Dissolution | Alytic | G | 0 | Good |
| | Eolytic | E-1 | −1 | Moderate |
| | Oligolytic | E-2 | −2 | |
| | Mesolytic | E-3 | −3 | Poor |
| | Hololytic | | −4 | |
| | | | −5 | Dissolution |

Figure 3. *Comparison of preservation categories of oceanic microfossils.*

The Late Cretaceous (late Maestrichtian) through early Eocene interval is represented at DSDP 163 by virtually barren brown clay and chert. Some rare reworked Cretaceous coccoliths occur in brown clay, but foraminifers and radiolarians are absent. The only fossiliferous sediment from the interval is at Site DSDP 162, directly above extrusive basalt. A richly diversified foraminiferal and coccolith assemblage of latest early Eocene age is characterized by moderate overgrowth on coccoliths (+2) instead of by solution. Foraminifers are well preserved, but radiolarians are sparse and poorly preserved. The presence of moderately solution-prone genera of coccoliths such as *Discolithina, Helicopontosphaera, Lophodolithus,* and *Syracosphaera* is consistent with deposition at relatively shallow rise-crest depths.

A fairly complete section of middle Eocene radiolarian and coccolith assemblages is preserved at Site DSDP 162. A similar well-preserved and well-diversified radiolarian-rich section is present at DSDP 163, but coccoliths are absent except at a single horizon. Foraminifers are absent at both sites. In DSDP 161A, a short section of late middle Eocene sediment contains abundant well-preserved radiolarians, common moderately dissolved coccoliths, and no foraminifers. Calcium carbonate content in these middle Eocene sections is low, usually less than 30 per cent. An absence of foraminifers and the presence of etched coccolith assemblages indicates deposition between a foraminifer-compensation depth, where all foraminifers are dissolved, and a coccolith-compensation depth below, where all coccoliths are dissolved. At most open-ocean sites, the coccolith-compensation depth is equivalent to the general calcite-compensation depth, because coccolith-producing organisms contribute the greatest bulk of solution-resistant calcitic material.

| Age | DSDP Site | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 68 | 69 | 163 | 76 | 70 | 71 | 42 | 41 | 162 | 161 | 40 | 72 | 73 | 74 | 75 | 77 | 160 | 78 | 159 | 79 | 80 | 81 | 82 | 83 |
| Holocene & Pleistocene | R | | | | D R | S D F C R | | | | | | S D F C R | S D F C R | S D F C R | C F | S D F C R | | | S D R | S D F C R | S D F C R | S D F C R | S D F C R | S D F C R |
| Pliocene | | | | C F | S D R | S D F C R | | | | | | S D F C R | S D F C R | D F C R | | S D F C R | | | | S D F C R | S D F C R | | S D F C R | S D F C R |
| Late Miocene | | | | ≠=== | S D R | S D F C R | | R | | | | S D F C R | S D F C R | R | | S D F C R | | | R | S D F C R | S D F C R | | S D F C R | S D F C R |
| Middle Miocene | | S D F C R | | | S D F C R | S D F C R | | | | | | S D F C R | D F C R | D F C R | | S D F C R | | F C R | C R | D F C R | S D F C R | F C R | v v v | S D F C R |
| Early Miocene | | S D F C R | | | D F C R | S D F C R | | | | C R | | S D F C R | F C R | D F C R | C F | S D F C R | C R | D F C R | F C R | D F C R | F C R | F C R | | v v v |
| Late Oligocene | | D F C R | R | | D F C R | D F C R | D F C R | | | D F C R | | D F C R | D F C R | F C R | C F | F C R | D F C R | S D F C R | F C | v v v | v v v | v v v | | |
| Early Oligocene | | S D F C R | R | | S D F C R | D F C R | D F C R | | D F C R | D F C R | | D F C R | S D F C R | F C | C F | D F C R | F C R | F C R | v v v | | | | | |
| Late Eocene | | S D F R | C R | | S D F C R | F C R | C R | R | D C R | C R | R | D F C R | D F C R | F C | v v v | F C | v v v | v v v | | | | | | |
| Middle Eocene | R | S D F R | C R | | * * * | * * * | D C R | R | D F C R | C R | C R | * * * | F C | F C | | v v v | | | | | | | | |
| Early Eocene | * * * | * * * | | | | | * * * | v v v | v v v | v v v | * * * | | = * = | v v v | | | | | | | | | | |
| Paleocene | | | | | | | | | | | | | | | | | | | | | | | | |
| Late Cretaceous | | | C R F v v v | | | | | | | | | | | | | | | | | | | | | |

Figure 4. *Occurrence of microfossil groups by age at East Pacific Rise sites. Sites arrayed from west (DSDP 68) to east (DSDP 83).* F, *foraminifers;* C, *coccoliths;* R, *radiolarians;* D, *diatoms; and* S, *silicoflagellates. Lithology at bottom of hole:* vvv *basalt,* *** *chert,* = = = *limestone.*

Late Eocene microfossil assemblages are dominated by abundant, well-preserved radiolarians; coccoliths are rare and strongly etched (-3 to -4), with most identifiable specimens centerless or broken. Foraminifers are absent, and most of the generally small quantities of calcium carbonate present – 0-1% at DSDP 163, 0-13% at DSDP 162, and 2-32% at DSDP 161A – is in the form of tiny particles, probably crystallites from disaggregated coccoliths.

Early Oligocene microfossil assemblages are dominated by coccoliths. This dramatic change from the Eocene is represented in sediment composition by significant increases in calcium carbonate all along the 140°W transect from DSDP 74 (6°S) to DSDP 162 (15°N).

DSDP Leg 16 sites have calcium carbonate contents in the lower Oligocene of 84-92% at DSDP 160, 86-96% at DSDP 161, 57-95% at DSDP 161A, and 1-87% at DSDP 162, increasing upward. Coccoliths show mixed preservation, wherein placoliths are slightly to moderately etched and discoasters are moderately to heavily overgrown by secondary calcite. Foraminifers are virtually absent; only a few limited assemblages occur, and solution has reduced these to the mesolytic dissolution facies. Radiolarians are common to abundant, as in the Eocene, but solution has been slightly stronger, and preservation is rated from moderate to good. In general, preservation of radiolarians is better where radiolarians are more abundant, as in rapidly accumulated low-carbonate deposits.

Through the late Oligocene and early Miocene, conditions similar to the early Oligocene persisted. Coccoliths are the dominant microfossil group, and calcium carbonate is abundant, percentages being slightly higher in the late Oligocene and slightly lower in the early Oligocene. Through this interval, coccolith preservation shows little variation; placcoliths are etched and discoasters overgrown. Foraminifers, although slightly more diverse than before, are still strongly affected by solution, and the assemblages are classified mesolytic. The most solution-resistant taxa are members of the genus *Catapsydrax* and *Globorotalia opima* s.l.; the least resistant are the small globigerinids of the *Globigerina ouchitaensis* group, and *Chiloguembelina, Cassigerinella,* and *Pseudohastigerina. Globigerina prasaepis* occurs quite commonly at all the eastern equatorial Pacific sites and seems to be moderately solution resistant. Although late Oligocene radiolarian preservation is similar to that of the early Oligocene, early Miocene radiolarians have been affected by stronger solution. Preservation is considered poor to moderate, and abundance decreases.

The youngest foraminifers preserved at the sites of DSDP Leg 16 occur at the shallowest site, DSDP 159, and are early Miocene. Coccoliths are preserved at the same site only as high as the middle Miocene. These coccolith deposits are strongly dissolved (-3) and composed mainly of discoasters; the coccolith horizons alternate with barren intervals near the top of their occurrence. Younger deposits sampled from the rise are barren of calcareous microfossils. Late Miocene to Holocene deposits are basically noncalcareous clays containing sporadic radiolarian assemblages. Some radiolarian horizons contain diverse and well-preserved assemblages; others have been reduced by solution to assemblages composed only of rare, highly resistant orosphaerid fragments (Dinkelman, this volume).

## REGIONAL CORRELATION

### Fossil Ages and Magnetic-anomaly Ages

Fifteen Deep Sea Drilling Project sites have been successfully cored to basalt in the equatorial part of the west flank of the East Pacific Rise (Table 1). At these sites, fossil zones and their approximate radiometric ages can be

**TABLE 1**
**East Pacific Rise Sites Cored to Basalt, Listed from East (DSDP 83) to West (DSDP 163). Estimated Age of Fossils in Basal Sediment is Considerably Less than Magnetic-Anomaly Ages for Older Sites, and Calculated Depths Based on Fossils are Generally Closer to Measured Depths. Calculated Depth to Basalt Utilizes the Composite Age/Depth Curve of Berger (1972). Magnetic Anomalies are Interpolated from Atwater and Menard (1970) and Herron (1972).**

| DSDP Site | Latitude | Longitude | Water Depth (m) | Basement Age Estimates | | | | Basement Depth (m) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Magnetic Anomaly | Age (m.y.) | Subepoch by Fossils | Age (m.y.) | Measured | Calculated from Age | |
| | | | | | | | | | Anomaly | Fossils |
| 83 | 4°02.80'N | 95°44.25'W | 3646 | 3 | (5) | L. Mio. | (8) | 3888 | 3400 | 3600 |
| 82 | 2°35.48'N | 106°56.52'W | 3707 | 5 | (10) | L. Mio. | (6) | 3921 | 3700 | 3500 |
| 81 | 1°26.49'N | 113°48.54'W | 3865 | 6 | (21) | E. Mio. | (15) | 4274 | 4200 | 3900 |
| [EM] | 28°58'N | 117°28'W | 3566 | 5 | (10) | M. Mio. | (14) | 3736 | 3700 | 3850 |
| 80 | 0°57.72'S | 121°33.22'W | 4411 | 6 | (21) | E. Mio. | (21) | 4610 | 4200 | 4200 |
| 79 | 2°33.02'N | 121°34.00'W | 4574 | 6 | (21) | E. Mio. | (21) | 4985 | 4200 | 4200 |
| 159 | 12°19.92'N | 122°17.27'W | 4484 | 8 | (29) | L. Olig. | (23) | 4593 | 4450 | 4250 |
| 78 | 7°57.00'N | 127°21.35'W | 4378 | 16 | (42) | E. Olig. | (35) | 4698 | 4850 | 4700 |
| 160 | 11°42.27'N | 130°52.81'W | 4940 | 20 | (49) | E. Olig. | (34) | 5054 | 5100 | 4650 |
| 77 | 0°28.90'N | 133°13.70'W | 4291 | 17 | (43) | L. Eoc. | (40) | 4772 | 4900 | 4800 |
| 75 | 12°31.00'S | 134°16.00'W | 4181 | 13 | (39) | E. Olig. | (33) | 4263 | 4750 | 4600 |
| 74 | 6°14.20'S | 136°05.80'W | 4431 | 20 | (49) | M. Eoc. | (45) | 4533 | 5100 | 5000 |
| 161 | 10°40.27'N | 139°57.27'W | 4939 | 26 | (64) | M. Eoc. | (45) | 5184 | 5400 | 5000 |
| 162 | 14°52.19'N | 140°02.61'W | 4854 | 25 | (63) | E. Eoc. | (49) | 5007 | 5350 | 5100 |
| 41 | 19°51.25'N | 140°02.88'W | 5337 | 27 | (67) | M. Eoc. | (48) | 5371 | 5450 | 5000 |
| 163 | 11°14.66'N | 150°17.52'W | 5320 | – | – | [E. Camp] | (78) | 5596 | – | 5600 |

related to the associated magnetic anomalies and their indicated ages. The magnetic anomalies are subdued and difficult to identify in this equatorial region (Herron, 1972); therefore the interpolated positions of the sites with respect to the magnetic-anomaly sequence are estimates. But as fossil zonations are especially well refined for equatorial assemblages, fossil ages are more consistent there than at high latitude, where the magnetic-anomaly patterns are better delineated.

At the younger eastern Pacific sites considered here, fossil and magnetic-anomaly ages agree fairly well, but at all sites where the bottom dates are Oligocene (23 m.y.) or older, magnetic ages are consistently older than the fossil ages (Figure 5). Magnetic ages tend to diverge further from fossil age for sites farther from the ridge crest. This divergence suggests a need to reevaluate the identification of magnetic anomalies in this region (van Andel and Heath, this volume) and the ages in years generally assigned to lower Cenozoic anomalies.

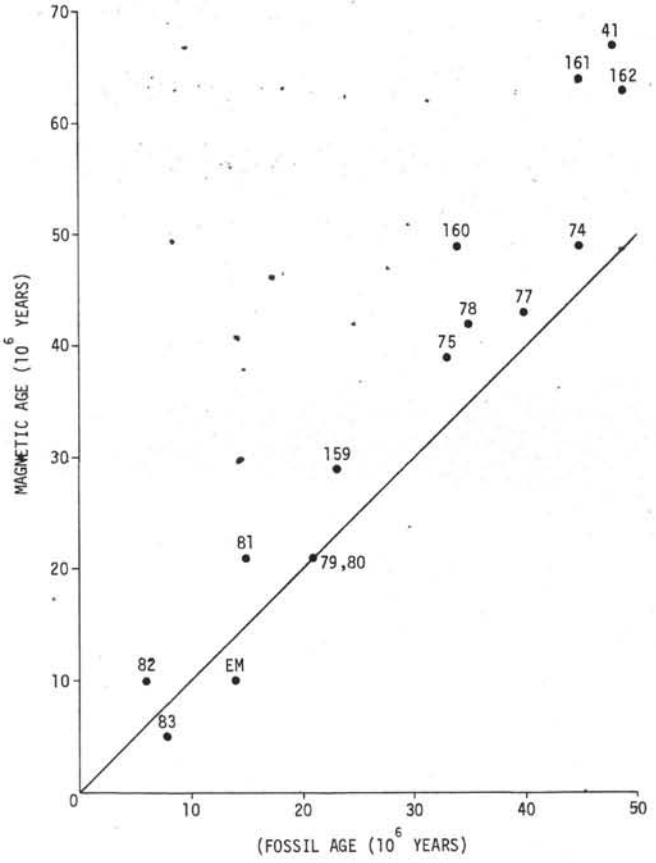


Figure 5. *Magnetic-anomaly age versus fossil age for sites cored to basalt on the west flank of the East Pacific Rise. Magnetic ages appear greater than fossil ages at older sites.*

### Basalt Depth versus Age

In addition to fossil- and magnetic-age determinations, the depth of the basement has been suggested as a relative gauge of age for ridge-flank sites (Menard, 1969; Sclater et al., 1971; and Berger, 1972). The hypothesis of age-depth constancy derives from a consistent cooling and contraction rate of basalt following ridge-crest emplacement. A plot of basement depth in relation to age for East Pacific Rise sites shows a general age-depth trend, but the data are quite scattered (Figure 6). Isostatic adjustment to thicker sediment sections might explain part of the difference. Sites of similar age but different thickness of cover show the isostatic effect but also display a residual scatter of unknown cause (Table 2). The data of this study suggest that the precision of Cenozoic basement-age estimates from depth is about ±15 m.y.

### Northward Motion of the Pacific Plate

A 30 degree northward component of movement of the northeastern Pacific during the Cenozoic has been suggested on the basis of paleomagnetic pole analyses (Francheteau et al., 1970). Such motion should be reflected in sediment thickness and in the composition of pelagic microfossil assemblages. The distinctive characters of highest equatorial pelagic productivity and tropical microfossil suites should be seen offset northward in progressively older sediment, because the climatic belt, fostering high productivity remains latitudinally centered. The location of thickest Cenozoic sections of equatorial sediment along the 140°W transect shows such an offset (Figure 7), and compatible thicknesses occur at other sites of the eastern equatorial Pacific.

Rotation resulting from a combination of northward motion and westward longitudinal motion from spreading at the margin of the plate could produce a northwestward-trending belt of thick former equatorial deposits. The pattern may be more complex if the change in plate motion indicated by the trace of the Hawaiian Islands hot spot is considered. Morgan (1972) has suggested, on the basis of Emperor and Hawaiian volcanic trends, that about 40 m.y. ago a change in Pacific plate motion resulted in a west-northwestward motion instead of the previous north-northwestward motion. Such a change is apparently reflected in the fossil and sedimentary record of the Eastern Equatorial Pacific. The major change in the northward translation rate of the axis of thickest sediment, however, is near the end of the Paleogene in late Oligocene time (23 to 30 m.y.). For the early Cenozoic, the northward component was about 0.5°/m.y., whereas the late Cenozoic translation was about 0.1°/m.y. The center of thickest pelagic sediment along the 140°W transect is offset to the north only slightly, about 3°, during the Miocene to Holocene (0 to 23 m.y.). This suggests that the northern component of the west-northwestward plate motion, indicated by the Hawaiian trend, was small, and thick equatorial sediment was left very near its original climatic latitude. About 5° of northward motion is indicated by location of the deposition centers of the Oligocene (23 to 38 m.y.). The thickest upper Eocene section is at 11°N, the thickest middle Eocene at 15°N, and the thickest lower Eocene at 20°N. Therefore, in this region a greater northward component is indicated for the Eocene (38 to 54 m.y.). The available data from DSDP sites in the Eastern Equatorial Pacific show the early Cenozoic equatorial belt of sediment to be more greatly offset to the north, thereby

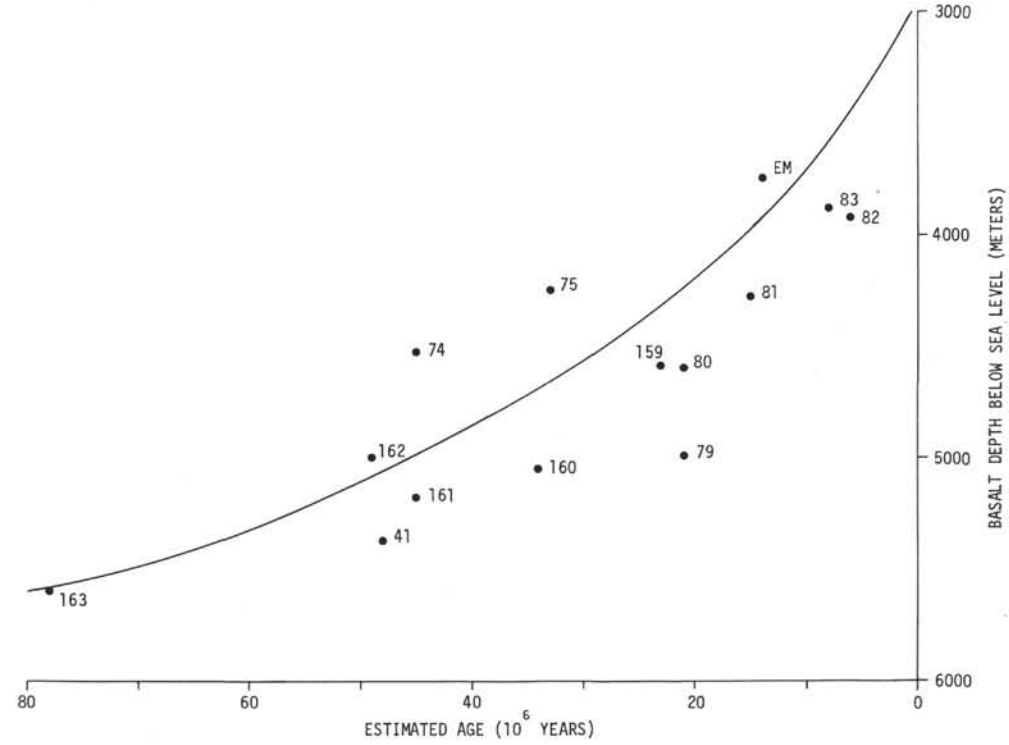


Figure 6. *Age-depth relation of basalt based on fossil ages at sites on the west flank of the East Pacific Rise. The average trend supports the observation of deepening basalt away from ridge axes by cooling, and Berger's (1972) age-depth curve has been added.*

**TABLE 2**
**Relation of Age, as Determined by Basalt-Basement Depth, to Sediment Thickness and Basal Fossil Age at DSDP 161 and DSDP 162**

| | DSDP 161 | DSDP 162 |
|---|---|---|
| Age from depth (m.y.) | 52 | 48 |
| Measured basement age (m.y.) | 45 | 49 |
| Basement depth (m) | 5184 | 5007 |
| Sediment thickness (m) | 245 | 153 |

supporting the hypothesis that north-northwesterly plate movement during the early Cenozoic accounts for the trend of the Emperor Seamounts. Approximately 20° of northward motion from Eocene to Holocene, a total of 54 m.y., is indicated by the occurrence of equatorial microfossil assemblages and by sediment thicknesses.

Dissolution of microfossils at depth can alter both the nature of resultant assemblages and the total thickness of sediment accumulated. For example, warm-water indicators such as discoasters and sphenoliths can be concentrated by differential solution. This suggests that an originally marginal subtropical assemblage could, in etched condition, resemble a tropical association. Therefore, thickness of pelagic sediment should be a central factor in determining present locations of ancient equatorial sediment. Thickness of geologic series and subseries based on DSDP sites in the Eastern Equatorial Pacific define the northward component of Pacific plate motion in the region (Figure 8).

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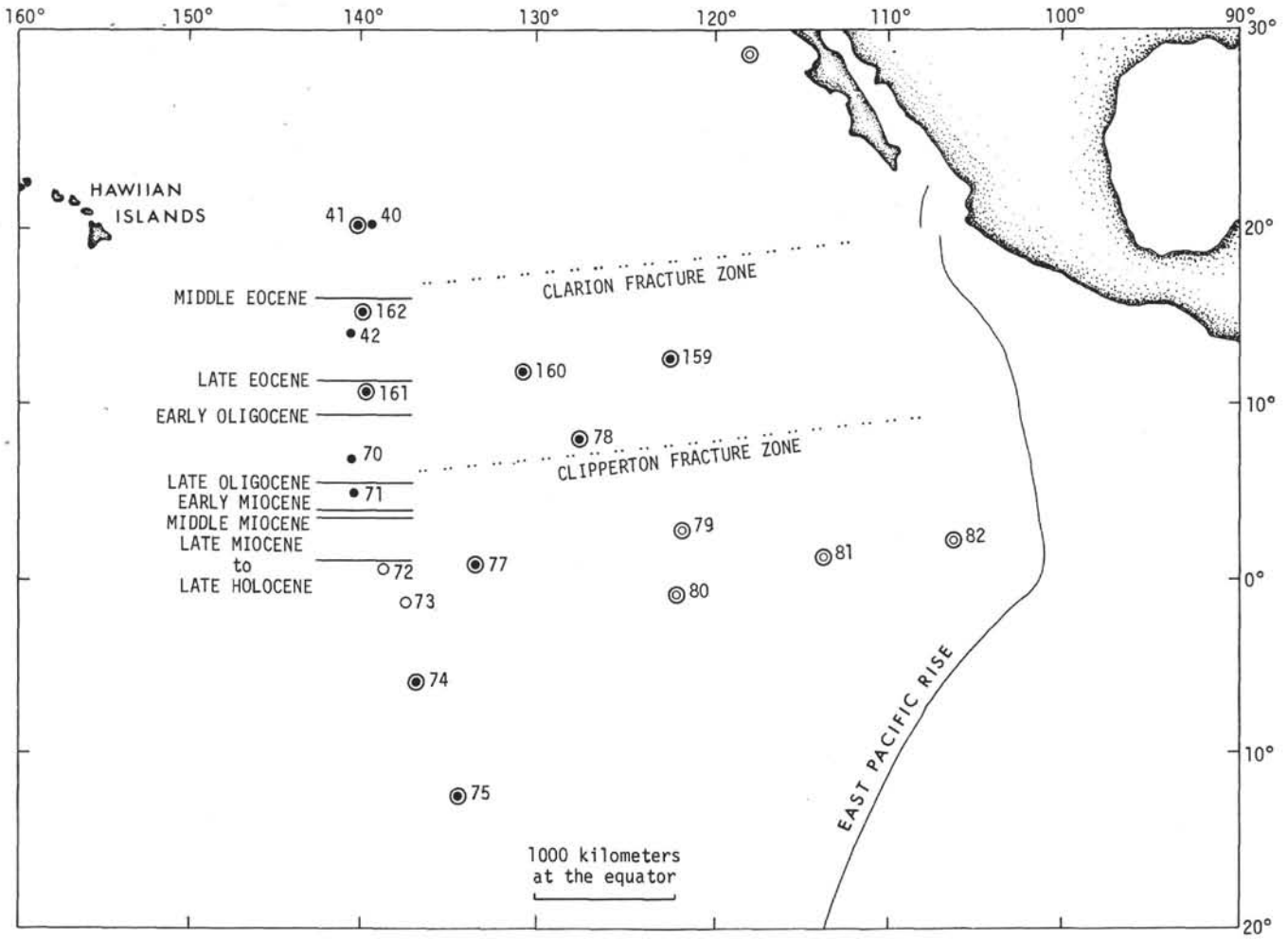


Figure 7. *Approximate location of axes of thickest sediment for various geologic subseries along the 140°W transect in the Eastern Equatorial Pacific.*


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| Series or Subseries | DSDP Site and Latitude | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 40 | 162 | 42 | 159 | 160 | 163 | 161 | 78 | 70 | 69 | 71 | 82 | 79 | 81 | 77 | 72 | 80 | 73 | 74 | 75 |
| | 19°48′ | 14°52′ | 13°51′ | 12°20′ | 11°42′ | 11°15′ | 10°40′ | 7°57′ | 6°20′ | 6°00′ | 4°28′ | 2°36′ | 2°33′ | 1°27′ | 0°29′ | Equator 0°26′N | 0°57′S | 1°55′ | 6°14′ | 12°31′ |
| Holocene & Pleistocene | | | | 9 | 8 | | | | 3 | | 9 | 37* | 13 | 41* | 27 | 22 | 23 | 15 | 9 | 1 |
| Pliocene | | | | | | | | | 5 | | 13 | 88* | 56 | 74* | 56 | 43 | 29 | 40 | | |
| Upper Miocene | | | | 9 | | | | | 12 | 4 | 39 | 98* | 80 | 138* | 82 | 67 | 32 | 17 | 3 | |
| Middle Miocene | | | | 18 | | | | 23 | 20 | 24 | 109 | | 127* | 127* | 67 | 62 | 25 | 37 | | |
| Lower Miocene | | | | 48 | 18 | | 18 | 117 | 67 | 24 | 175* | | 138* | 29 | 85 | 72 | 97 | 54 | 22 | 33 |
| Upper Oligocene | | | 13 | 25 | 45 | 19 | 90 | 98 | 136* | 64 | 154* | | | | 94 | 64 | | 85 | 34 | 27 |
| Lower Oligocene | 5 | 36 | 22 | | 22 | 9 | 90 | 82* | 64 | 28 | 44 | | | | 52 | 10 | | 38 | 19 | 21 |
| Upper Eocene | 75* | 18 | 27* | | | 18 | 30 | | 5 | 18 | 13 | | | | 11 | 5 | | 11 | 8 | |
| Middle Eocene | 64* | 90* | 46 | | | 50 | 15 | | | 69 | | | | | | | | 3 | 1 | |
| Lower Eocene | | 9* | | | | | | | | | | | | | | | | | | |

Figure 8. *Approximate sediment thickness in meters of geologic series and subseries for DSDP sites on the flank of the East Pacific Rise, based on a unified biostratigraphy. Geologic series may be abbreviated at the top and bottom of cored sections by erosion, deposition on basalt, or undrillable chert horizons. In discontinuously cored intervals, sedimentation rates are used to estimate boundary positions; correction was not made for reduced porosity due to compaction. Sites are arrayed from north (DSDP 40) to south (DSDP 75). Thickest Paleogene sediments are between 4°N and 20°N; thickest Neogene between 1°N and 4°N. First and second thickest sections of each subseries are indicated by asterisk.*

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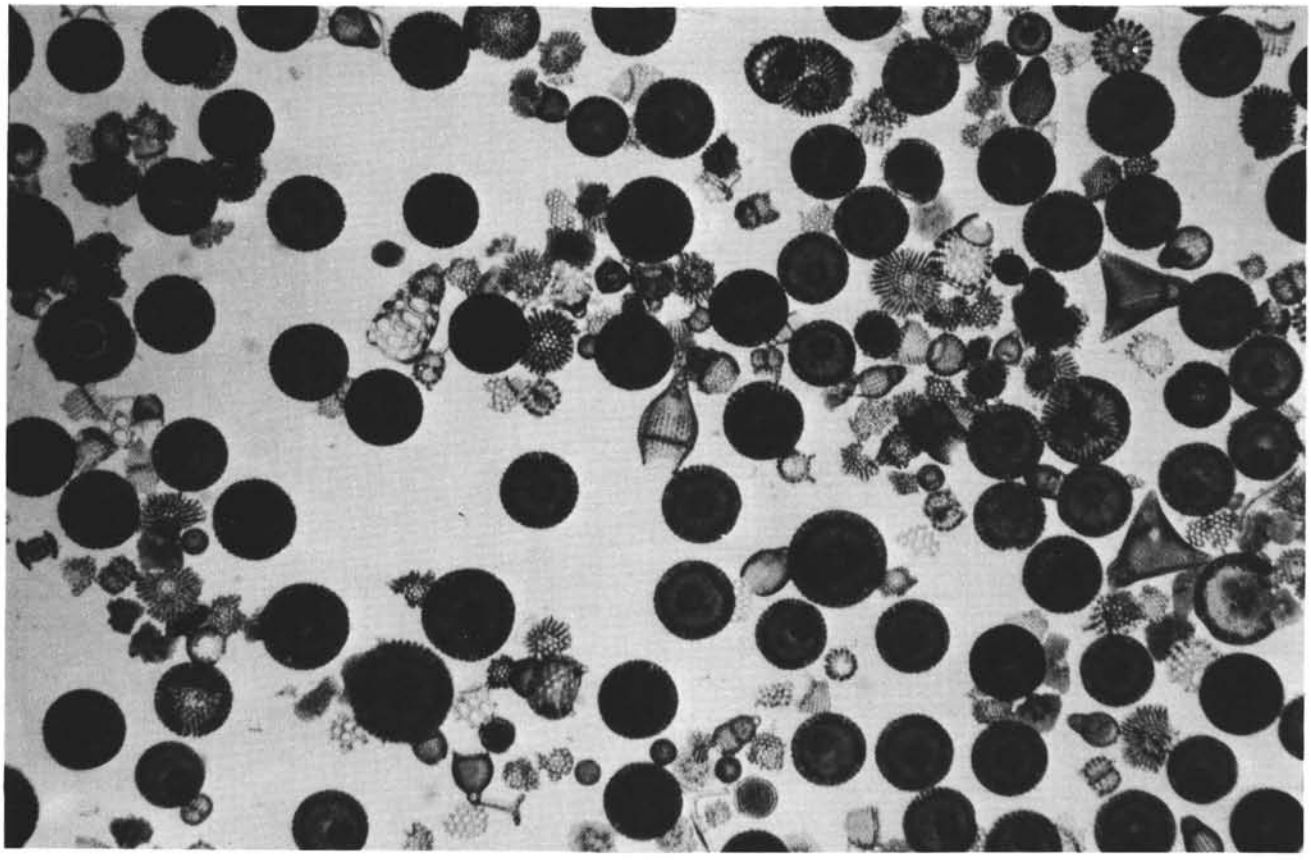
PLATE 1

Abundance of a sphaeroid radiolarian, probably *Periphaena decora* Ehrenberg, in samples from the top of the middle Eocene *Podocyrtis chalara* Zone. Photomicrographs magnified 35 X. Scale bar equals 300 microns.

Figure 1 — *Periphanena decora* especially abundant. Sample DSDP 161A-13A (CC) (228 m).

Figure 2 — *Periphaena decora* abundant. Sample DSDP 162-7 (CC) (63 m).

PLATE 1



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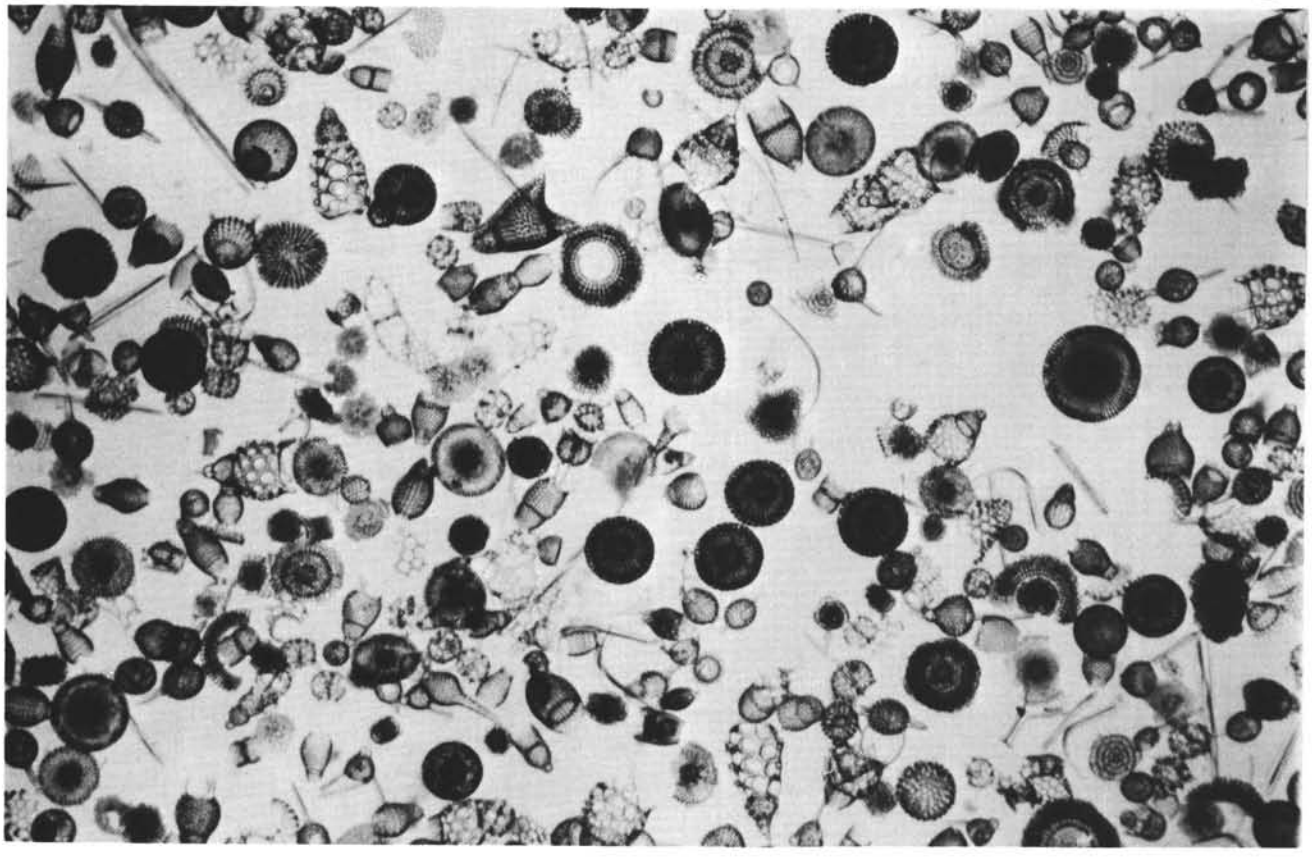

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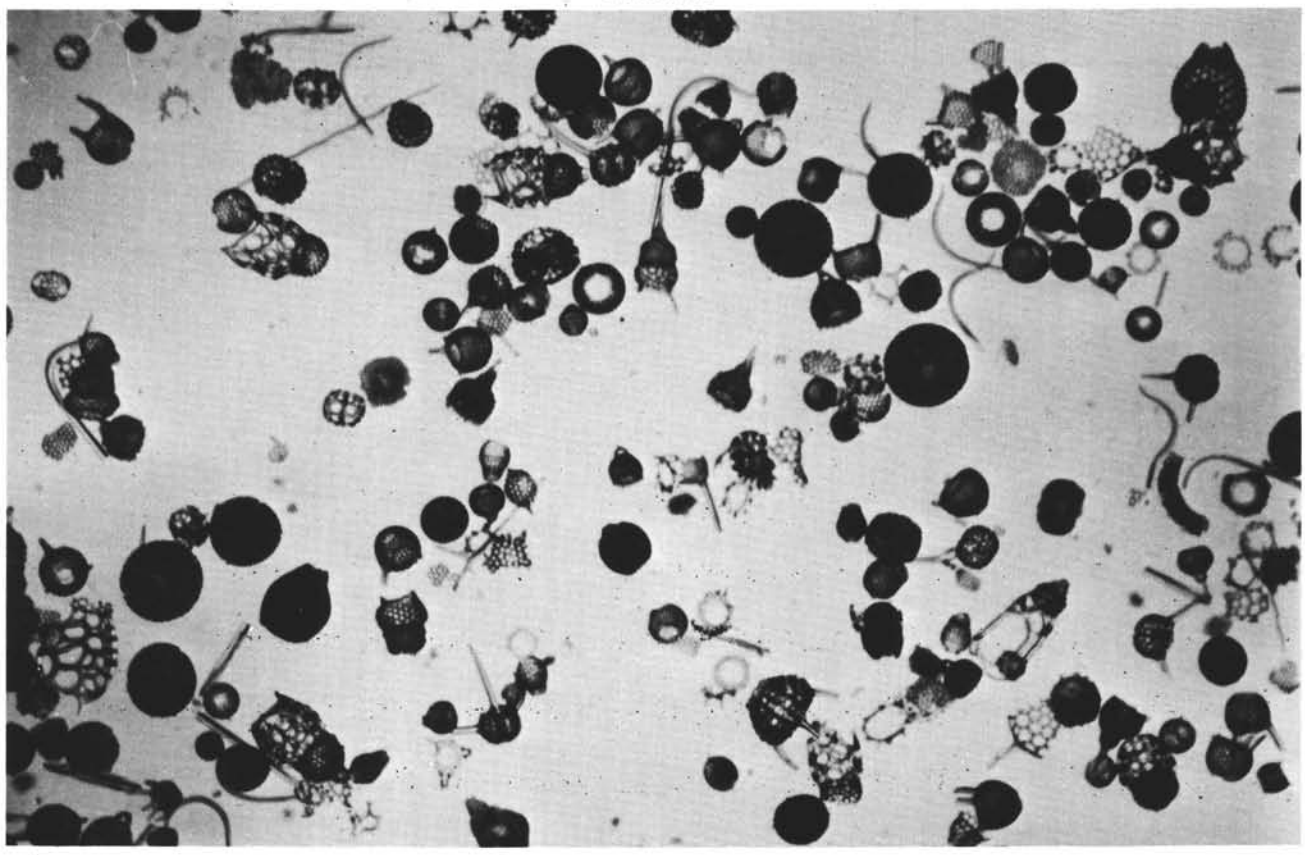
PLATE 2

The occurrence of the sphaeroid radiolarian *Periphaena decora* in assemblages from the Eocene lower *Podocyrtis goetheana* Zone and the upper *Podocyrtis chalara* Zone. Photomicrographs magnified 35 X. Scale bar equals 300 microns.

Figure 1 — *Periphaena decora* common in *Podocyrtis goetheana* Zone. Early forms of *Thyrsocyrtis bromia* occur but their occurrence is probably due to vertical mixing. Sample DSDP 163-6-6 (120-123 cm) (46 m).

Figure 2 — *Periphaena decora* common to abundant in *Podocyrtis chalara* Zone. Sample DSDP 163-7-1 (120-123 cm) (47 m).

PLATE 2



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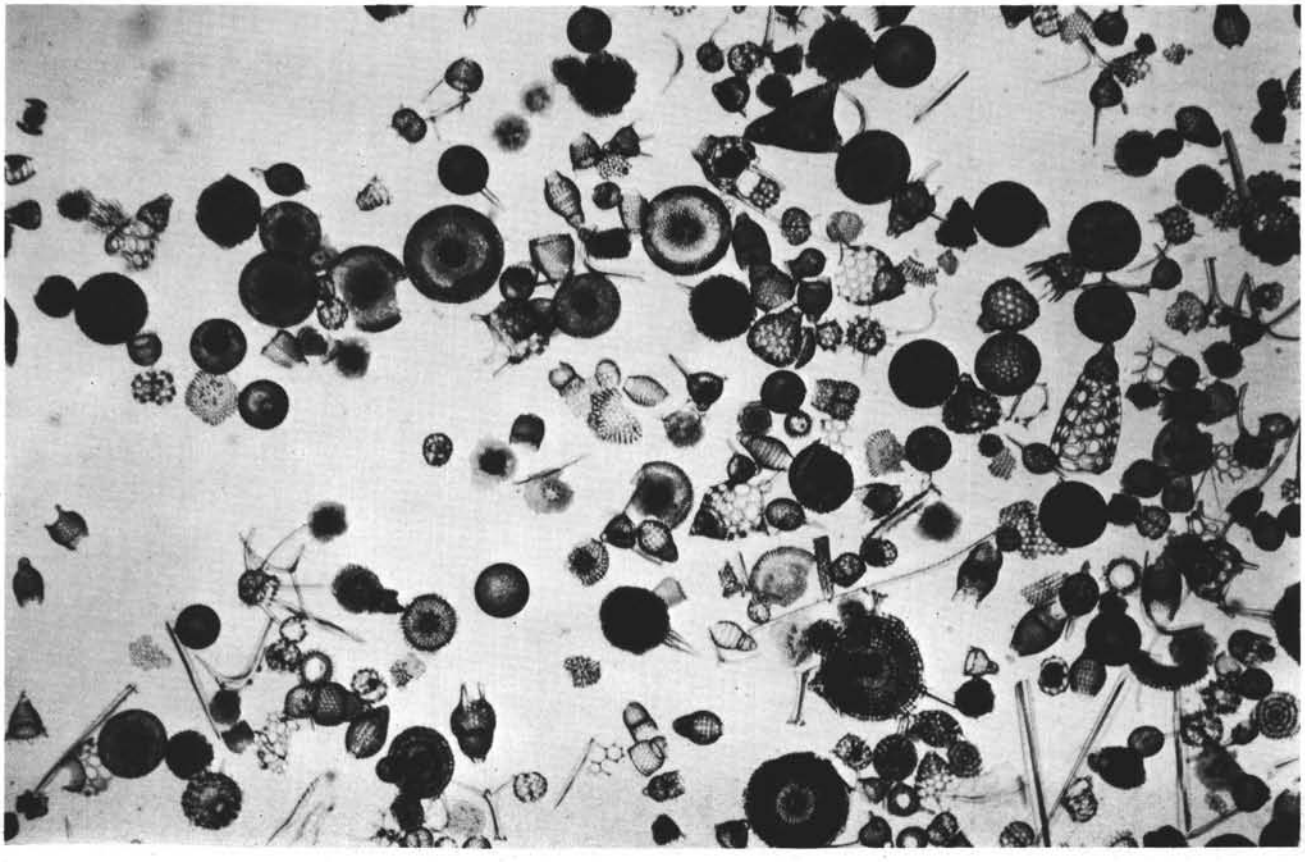


PLATE 3

*Discoaster* specimens from the East Pacific Rise in various stages of preservation. Photomicrographs magnified 1000 X. Scale bar equals 10 microns.

Figure 1 — *Discoaster asymmetricus* Gartner
Sample DSDP 77B-4B-4 (66-67 cm) (42 m).

Figure 2 — *Discoaster barbadiensis* Tan
Sample DSDP 162-14-1 (40-41 cm) (117 m).
Two etched specimens; preservation stage of assemblage and smaller specimen (-3) that of larger specimen (-4).

Figure 3 — *Discoaster bellus* Bukry and Percival
Sample DSDP 83-7-5 (100-101 cm) (227 m).

Figure 4 — *Discoaster berggrenii* Bukry
Sample DSDP 83A-15A-6 (130-131 cm) (189 m).

Figures 5-7 — *Discoaster* (sp. cf. *D. challengeri* Bramlette and Riedel
Sample DSDP 77B-18B-6 (73-74 cm) (173 m).
5. Thickly-overgrown stage (+3); form of ray-tips, rays, and central area obscured. Incipient overgrowth of rays across central area forms a triad in six-rayed species. A more pronounced overgrowth triad is shown in Figure 12 for *Discoaster kugleri.*
6-7. Moderately-overgrown stage (+2); original ray-form, appearing as ridges, and ray-tip form can be observed for most rays.

Figure 8 — *Discoaster decorus* (Bukry)
Sample DSDP 82-2-4 (63-64 cm) (74 m).
Slightly-etched stage (-1).

Figure 9 — *Discoaster deflandrei* Bramlette and Riedel
Sample DSDP 159-5-2 (120-121 cm) (39 m).
Typical Six-rayed specimen and asymmetric five-rayed variant. Overgrowth stage (+2); interray rounded outlines still present.

Figure 10 — *Discoaster druggii* Bramlette and Wilcoxon
Sample DSDP 159-8-6 (120-121 cm) (72 m).
Differential overgrowth on same specimen; nodes and camber on three of the rays are obscured.

Figures 11-12 — *Discoaster kugleri* Martini and Bramlette
Sample DSDP 70-3-3 (63-64 cm) (21 m).
Differential overgrowth in same sample.
11. (+1).
12. (+3) with overgrowth triad.

Figure 13 — *Discoaster loeblichii* Bukry
Sample DSDP 83A-16A-4 (64-65 cm) (215 m).

Figure 14 — *Discoaster pansus* (Bukry and Percival)
Sample DSDP 83A-16A-4 (64-65 cm) (215 m).

Figures 15-16 — *Discoaster quinqueramus* Gartner
Sample DSDP 83A-12A-4 (63-64 cm) (119 m).

Figures 17-18 — *Discoaster surculus* Martini and Bramlette
Sample DSDP 83A-12A-4 (63-64 cm) (119 m).

Figure 19 — *Discoaster tamalis* Kamptner
Sample DSDP 77B-4B-6 (70-71 cm) (45 m).

Figure 20 — *Discoaster* sp. cf. *D. variabilis* Martini and Bramlette
Sample DSDP 77B-5B-3 (70-71 cm) (49 m).
Unusual five-rayed variant having six-rayed symmetry.

**PLATE 3**

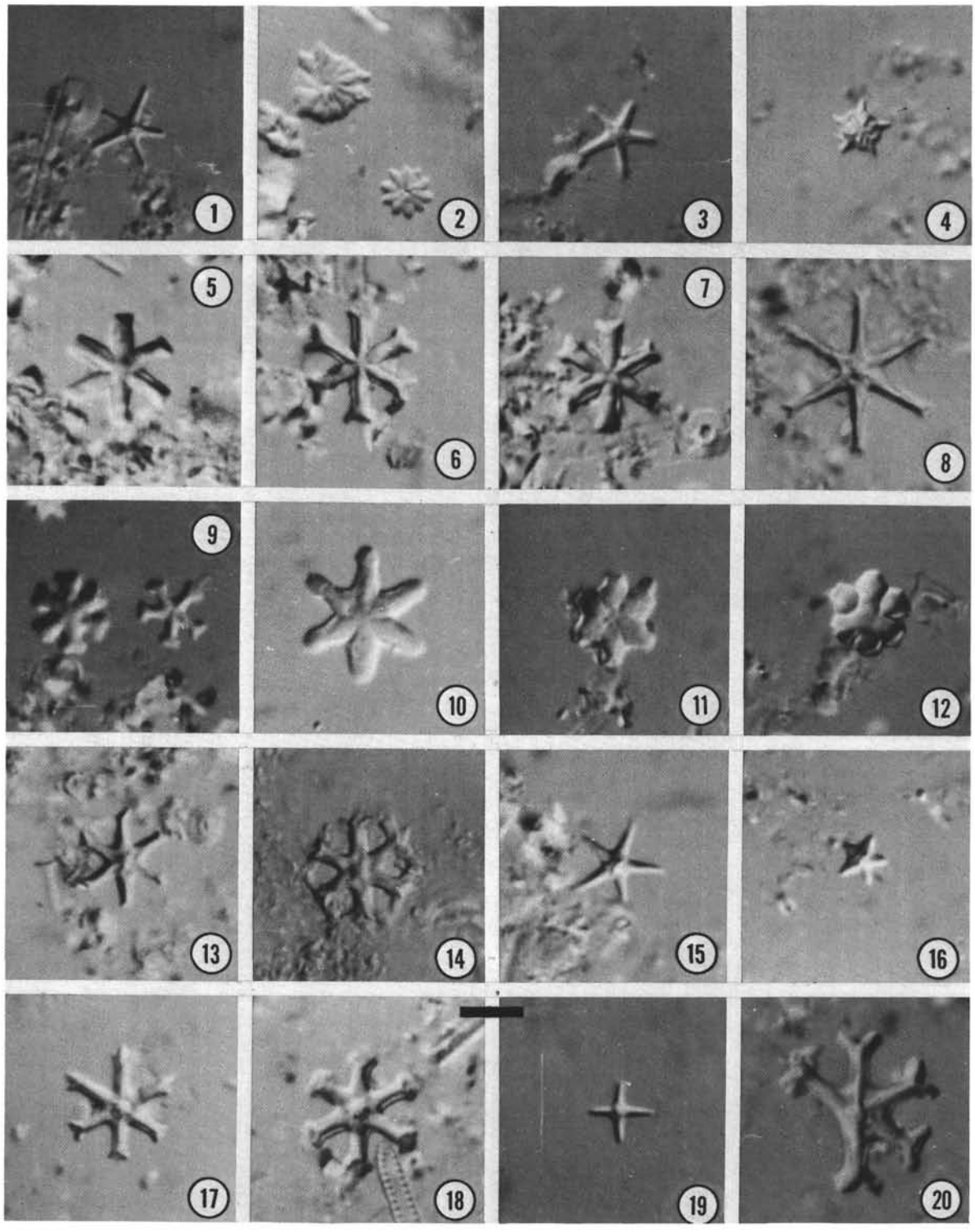


PLATE 4

Different preservation stages of two radiolarian taxa from the Oligocene, *Artophormis gracilis* (Figures 1-10) and *Theocyrtis annosa* (Figures 11-14). Photomicrographs magnified 200 X. Scale bar equals 50 microns.

*Artophormis gracilis* Riedel

Figure 1 — Very good preservation, rarely in this state.
Sample DSDP 161A-7A-5 (124-126 cm) (180 m).

Figures 2-3 — Good preservation.
2. Sample DSDP 161A-8A-1 (134-136 cm) 183 m).
3. Sample DSDP 161A-7A-5 (124-126 cm) (180 m).

Figure 4 — Moderately good preservation.
Sample DSDP 161A-8A-1 (134-136 cm) (183 m).

Figure 5 — Moderate preservation.
Sample DSDP 161A-6A-3 (125-128 cm) (168 m).

Figures 6-8 — Poor to moderate preservation
6-7. Sample DSDP 161A-6A-3 (125-128 cm) (168 m).
8. Sample DSDP 160-10-3 (124-126 cm) (85 m).

Figures 9-10 — Poor preservation.
Sample DSDP 160-10-3 (124-126 cm) (85 m).

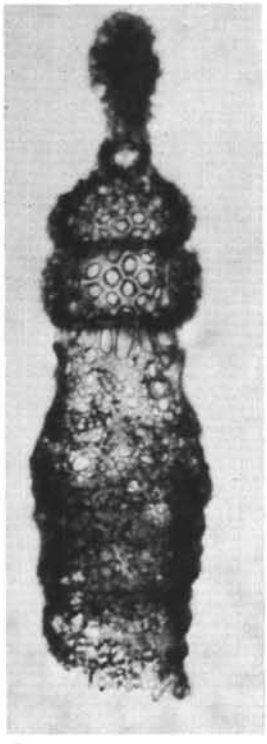
*Theocyrtis annosa* (Riedel)

Figure 11 — Good preservation.
Sample DSDP 161A-1A-1 (56-59 cm) (64 m).

Figure 12 — Moderate preservation.
Sample DSDP 161-10-3 (125-128 cm) (85 m).

Figures 13-14 — Poor preservation.
Sample DSDP 161-7-3 (118-120 cm) (58 m).

PLATE 4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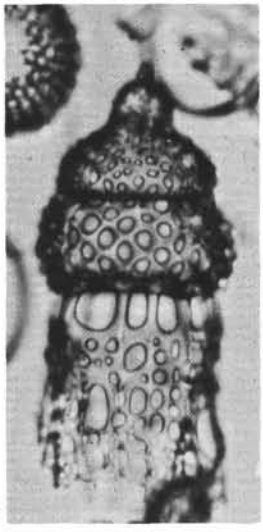
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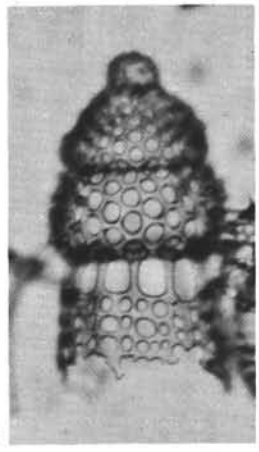
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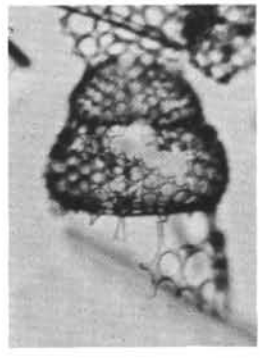
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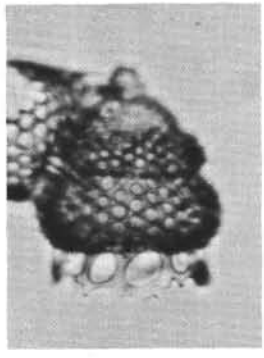
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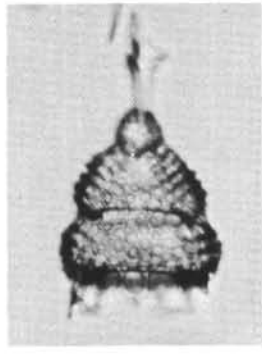
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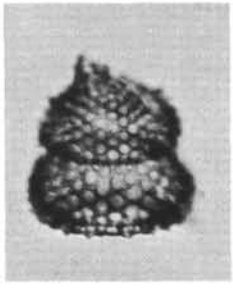
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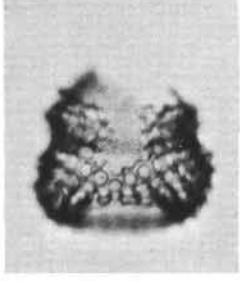
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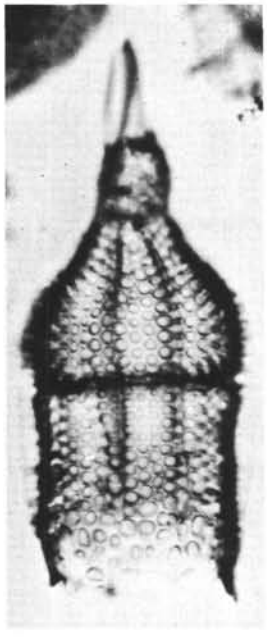
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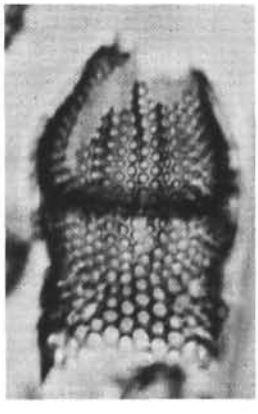
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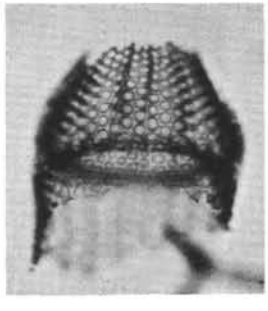
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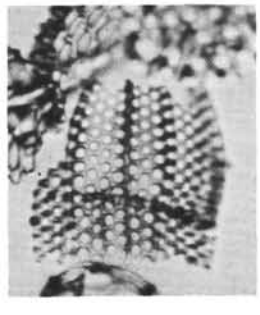
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