4. Oligocene Calcareous-Nannofossil Biostratigraphy from Leg 101, Site 628, Little Bahama Bank Slope

Michael J. Moran and David K. Watkins

ABSTRACT

Drilling at Hole 628A, Leg 101 of the Ocean Drilling Program, recovered a thick, relatively complete Oligocene section of nannofossil-foraminifer chalk and ooze. Sediments from Cores 101-628A-16H through 101-628A-29X were examined using the light microscope to provide information about biostratigraphy of calcareous nannofossils. Several authors noted a problem in distinguishing the first appearance of species within the Sphenolithus predistentus-S. ciperoensis lineage of the mid-Oligocene, particularly Sphenolithus ciperoensis, because of the gradual evolution of its members. Successful separation of species in this lineage is critical for accurately dating relative age of mid- and upper-Oligocene nannofossil sediments. Length and taper of the apical spine, along with width of the proximal shield, were reported by various authors as the best criteria for separating S. ciperoensis from Sphenolithus distentus in light microscopy. We find that the "extinction" line characteristics of the proximal shield, as originally proposed, are the best criteria for separation in light microscopy. These criteria provide results that correlate well with dating using other microfossils. Scanning electron microscopy (SEM) study shows that this feature directly results from the widening of the proximal shield during evolution from S. predistentus to S. ciperoensis. Transitional forms between S. distentus and S. ciperoensis show features of both species. The last appearance datums (LAD) of Lanternisthurna minutus and Helicopontosphaera compacta were found to correspond with the first appearance datum (FAD) of S. ciperoensis in Hole 628A. The LAD of H. compacta has a high confidence rating for reliability as an alternative datum to the FAD of S. ciperoensis. The usefulness of L. minutus to approximate this datum is much less. Other potentially useful Oligocene nannofossil datums (with varying degrees of usefulness) also are given.

INTRODUCTION

Drilling at Hole 628A, Leg 101 of the Ocean Drilling Program, recovered a thick, relatively complete section of Oligocene nannofossil-foraminifer chalk and ooze. This section allowed us to examine the Oligocene nannofossil biostratigraphy in detail, particularly the mid-Oligocene, where a number of problems have arisen repeatedly regarding the Sphenolithus predistentus-Sphenolithus ciperoensis nannofossil lineage. Several authors noted a problem when working with the mid-Oligocene sphenoliths (e.g., Roth et al., 1971a, 1971b; Haq, 1972; Lang and Watkins, 1984) because of the slow evolution of this lineage. A major problem is to distinguish the FAD of Sphenolithus ciperoensis because of its gradual evolution from Sphenolithus distentus. Recognizing the FAD of members of this lineage is important for placing mid-Oligocene pelagic sediments containing nannofossils in the proper zone and, thus, for accurately dating relative age. Hole 628A contained a thick section in the S. ciperoensis Zone (Cores 101-628A-16H through 101-628A-24X) that allowed us to study the S. distentus-S. ciperoensis transition in detail. We focused special attention on these two species in hopes of clarifying distinguishing characteristics for better taxonomic separation. In addition, the last appearances of other nannofossil species were considered as alternatives to the sphenolith datums.

Hole 628A was located at 27°31.85'N, 78°18.95'W, north of the Little Bahama Bank at the bank toe-of-slope in 966 m of water (Fig. 1). Holes 628A, 627, 629, and 630 were part of a transect of the Little Bahama Bank. Total penetration at the site was 298.4 m. Sediments ranging from upper Paleocene through Eocene sphenoliths (e.g., Roth et al., 1971a, 1971b; Haq, 1972) because of its gradual evolution from Sphenolithus distentus. A major problem is to distinguish the FAD of members of this lineage. Recognizing the FAD of Sphenolithus ciperoensis because of its gradual evolution from Sphenolithus distentus. Lithologically, Cores 101-628A-16H through 101-628A-23X and Cores 101-628A-27X through 101-628A-29X consisted predominantly of foraminifer-nannofossil chalk and ooze. Cores 101-628A-24X through 101-628A-26X consisted predominantly of varying proportions of nannofossil-foraminifer chalk and ooze and lithified or partially lithified packstones and floatstones. Bioturbation was indicated in all cores in varying amounts (Austin, Schlager, et al., 1986).

METHODS AND PROCEDURES

Calcareous-nannofossil assemblages from samples of Cores 101-628A-16H through 101-628A-29X were examined using the light microscope to provide information about biostratigraphy. Results from the examination of smear slides prepared from raw-sediment samples are presented in Table 1. This table shows the relative abundance of each nannofossil taxon, its distribution, and an estimate of its preservational state in each core sample examined. Estimation of abundance and preservation of individual nannofossil species follows Hay (1970), as modified by Watkins and Bowdler (1984). Abundances for individual nannofossil taxa in Table 1 are as follows: A, abundant (1–10 specimens per field of view at 1500x); C, common (1 specimen per 2–10 fields of view at 1500x); F, few (1 specimen per 11–100 fields of view at 1500x); R, rare (1 specimen per 101–1000 fields of view at 1500x), questionable presence of the species.

Our method for estimating the abundance of nannofossils as a sedimentary component was taken from Watkins and Bowdler (1984). All except one sample (Sample 101-628A-23X-2, 95–100 cm) contained abundant nannofossils (>15%). In this sample, nannofossils are diluted by a large component of quartz silt. Several samples of periplatform ooze within the section contained abundant micrite debris, while still having abundant (more than 15%) nannofossils. These samples are denoted by the letter "P" in the abundance column of Table 1.
Preservation of nannofossils in any given sample varies greatly. An "average" state of preservation was assigned to each sample, based on the following method, which follows Watkins and Bowdler (1984). G (good) = most specimens exhibit little or no secondary alteration; M (moderate) = specimens exhibit the effects of secondary alteration caused by etching and/or overgrowth (identification of species is not impaired); P (poor) = specimens exhibit profound effects of secondary alteration from etching and/or overgrowth (identification of species is impaired but possible). In general, preservation is good to moderate throughout, with only one sample (101-628A-23X-2, 95-100 cm) exhibiting poor preservation of nannofossils.

Biostratigraphic zonation of the samples follows Bukry (1973a, 1975) and Okada and Bukry (1980). Their scheme was used because it gives the highest resolution for the Oligocene and is more applicable to tropical regions. The good recovery in many of the cores allowed us to recognize most of the Oligocene zones and subzones of Okada and Bukry (1980). Zonal and subzonal names were modified to conform with the taxonomy used here.

RESULTS

Results about the relative abundance, preservation, and distribution of nannofossils from examination of Hole 628A core samples are presented in Table 1. At the top of the studied interval, Samples 101-628A-16H-1, 80-81 cm through 101-628A-23X, CC are assigned to the Dictyococcites bisectus Subzone (CP19b) of the Sphenolithus ciperoensis Zone (CP19). This subzone is clearly delineated by the last appearance of S. distentus, which occurs in Sample 101-628A-24X-1, 80-81 cm. Typical species for this subzone include Coccolithus eopelagicus, Coccolithus pelagicus, Coronocyclus nitescens, Cyclicargolithus abisectus, Cyclicargolithus floridanus, Discoaster deflandrei, Ericsonia fenestrata, Helicopontosphaera euphratis, H. recta, Dictyococcites bisectus, Sphenolithus ciperoensis, and S. moriformis. No important datums were observed in this subzone.

Sample 101-628A-24X-1, 80-81 cm, is assigned to the Cyclicargolithus floridanus Subzone (CP19a) of the Sphenolithus ciperoensis Zone (CP19). This subzone was defined by Bukry (1975) on the basis of the co-occurrence of S. ciperoensis and S. distentus. Sphenolithus distentus is present only in low abundance levels in this sample. The thinness of this subzone and the underlying Sphenolithus distentus Zone indicates that a hiatus may be present in this part of the section. Typical nannofossil species are the same as for the overlying subzone, with the addition of S. distentus. The last appearances of Helicopontosphaera compacta and Lanterninithus minutus occur in Section 101-628A-24H, CC, which corresponds to the first appearance of S. ciperoensis at the base of the subzone. The last appearance of H. compacta may be a useful datum for approximating the first appearance of S. ciperoensis, which is discussed later. The LAD of L. minutus is less useful for approximating this datum.

Although the Cyclicargolithus floridanus Subzone is thin, the boundary between it and the underlying Sphenolithus distentus Zone (CP18) is difficult to delineate in this section. The original criteria for the Sphenolithus distentus Zone was the stratigraphic interval from the FAD of S. distentus to the first evolutionary appearance (FAD) of S. ciperoensis (Bukry, 1973a). However, previous workers noted a problem with the gradualistic nature in the evolution of the sphenoliths during the Oligocene, making the distinction of the FAD of S. ciperoensis difficult (Roth et al., 1971a, 1971b; Haq, 1972; Lang and Watkins, 1984). This problem also was encountered in the Oligocene section from the northern slope of Little Bahama Bank with forms that are transitional between S. distentus and S. ciperoensis occurring to the top of CP19. This caused confusion regarding the LAD of S. distentus and the exact taxonomic criteria for separating these species. A method for resolving this problem is discussed later. Using this methodology, we were able to make the following biostratigraphic subdivision of the section: Section 101-628A-24X, CC through Sample 101-628A-25X-2, 80-81 cm, are assigned to the S. distentus Zone (CP18). The base of the zone is clearly marked by the first appearance of S. distentus, while the top corresponds to the first appearance of S. ciperoensis. The taxonomic composition of assemblages in this interval is similar
to those in the overlying zone, with the addition of H. compacta and L. minutus.

Although this zone is thin (= 3 m) at this site, several important nannofossil datums can be recognized in it. The first common appearance of Cyclococcolithus abisectus occurs in Sample 101-628A-25X-1, 80–82 cm. Discoaster tani becomes extinct and D. adamanteus first appears near the FAD of S. distentus in Sample 101-628A-25X-2, 80–81 cm. Sphenolithus pseudoradians also become extinct in Sample 101-628A-25X-2, 80–81 cm. In some areas, the LAD of D. tani and the FAD of D. adamanteus might be useful for approximating the first appearance of S. distentus, respectively.

The last appearance of S. predistentus occurs in Section 101-628A-24X, CC, slightly before the last appearance of S. distentus in Sample 101-628A-24X-1, 80–81 cm. Perch-Nielsen (1985) stated that it is common for S. predistentus to disappear before the last appearance of S. distentus. Specimens of S. predistentus occur as high as Sample 101-628A-21H-3, 80–81 cm, in this section.

The thinness of the Sphenolithus distentus Zone, along with the disappearance of S. pseudoradians and several other nannofossils at the base of the zone, might indicate that part of this zone is missing. This idea gains credence because Lang and Watkins (1984) noticed a gradual change from S. predistentus to S. distentus in Oligocene material from DSDP Leg 77. This change also was observed by Moran (in Watkins et al., this volume) in material from Site 540, Leg 77, which suggests that a gradual change exists between these two species, as between S. distentus and S. ciperoensis. This gradual change was not observed in material from Hole 628A because S. distentus appears suddenly. No transitional forms between S. distentus and S. predistentus were found. The lack of expression of a gradual transition between these two species may result from missing material because of an unconformity.

Section 101-628A-25X, CC through Sample 101-628A-27X-2, 80–81 cm, are assigned to the Sphenolithus predistentus Zone (CP17), which approximates the transition from upper to lower Oligocene. This zone is defined as the stratigraphic interval between the FAD of S. distentus to the LAD of Reticulofenestra hillei and R. umbilica (Bukry, 1973a). A typical assemblage of this zone from Hole 628A includes Bramlettei serraculoides (leve), Calcidiscus protoanulina, Coccolithus eopelagicus, Coccolithus pelagicus, Coronocyclus nitescens, Cyclolithus floridanus, Discoaster deflandrei, D. tani, D. nodifer, Hayella sititiformis, Helicopontosphaera compacta, Isthmolithus recurvus (basal subzone), Dictyococcites bisectus, R. hillae, R. umbilicala, Sphenolithus moriformis, S. predistentus (few), and S. pseudoradians. Numerous specimens of the genus Pemma occur in the lowermost part of the subzone (Sample 101-628A-29X/2, 47–48 cm), but decrease in abundance until they disappear above Sample 101-628A-28X-2, 80–81 cm. The majority of these braarudosphaerids occur as fragments. In general, braarudosphaerids are most common in samples near the Eocene/Oligocene boundary in Hole 628A. Rare specimens of Discoaster saipanensis occur in samples near the base of the H. reticulata Zone in Samples 101-628A-29X-2, 47–48 cm, and 101-628A-29X-1, 80–81 cm. Their sparseness and poor preservation strongly suggest that these specimens were reworked.

The Sphenolithus predistentus–S. ciperoensis Lineage

Bramlette and Wilcoxon (1967) were the first to recognize the biostatigraphic utility of sphenoliths in the Oligocene and successfully applied it in naming three mid-Oligocene nannofossil zones. Separation of these zones is based on the evolution of the Sphenolithus predistentus–S. ciperoensis nannofossil lineage. The evolution of this sphenolith lineage provides three important datum levels for nannofossil zonal boundaries in normally low-diversity, mid-Oligocene nannofossil assemblages. These sphenoliths are useful because few other groups of nannofossils undergo significant evolution during this time. Unfortunately, the S. predistentus–S. ciperoensis lineage undergoes a slow, gradual evolution, and the usefulness of these zones is often masked by the difficulty many workers found when distinguishing the first appearances of cohort species using the light microscope.

Bramlette and Wilcoxon (1967) realized the gradual nature of the evolution of this lineage and noted problems with separation of species in light microscopy, particularly S. distentus and S. ciperoensis. These sphenolith zones have since been widely used, and other workers noted the gradual evolution of this lineage and associated problems of separation of species using the light microscope (Roth et al., 1971a, 1971b; Haq, 1972; and Lang and Watkins, 1984). Most of these authors specified the difficulty when separating S. ciperoensis from S. distentus. Haq (1972) recognized this problem, as did Lang and Watkins (1984), who created the informal taxon Sphenolithus sp. cf. S. ciperoensis to include transitional forms. Lang and Watkins also noted a problem with distinguishing Sphenolithus distentus from S. predistentus in core material from the Straits of Florida (DSDP Leg 77) because of a number of specimens having an intermediate construction.
In addition to the gradual evolution of this group, problems of paleogeography complicate its use. Sphenoliths are more common in lower latitudes than in high latitudes (Edwards, 1971). Perch-Nielsen (1972) suggested that they were more common in relatively shallow-water paleoenvironments, as opposed to deep-marine ("open-ocean") paleoenvironments. In general, these problems suggest the need for more exact taxonomic criteria and/or the use of an alternative set of biostatigraphic indicators.

Identifying the FAD of *S. distentus* was not difficult using material from Hole 628A because transitional forms between *S. predistentus* and *S. distentus* are rare. As pointed out previously, this may indicate missing material here because of the gradual change other workers noticed between these two species (Lang and Watkins, 1984). The thickness of the *S. distentus* Zone and the *C. floridanus* Subzone, as well as the occurrence of several coextinct extinctions, also points to an unconformity or unconformities in this part of the section from Hole 628A.

Separation of *S. ciperoensis* from *S. distentus* in Hole 628A was more difficult, with intermediate forms occurring from Sample 101-628A-24X-1, 80-81 cm, through 101-628A-16H-1, 80-81 cm. Table 2 compares and contrasts various author's descriptions of the structure and morphology of *S. distentus* and *S. ciperoensis* using both light and electron optical systems. A review of the more distinguishing characteristics of both species (as discerned here) is presented in Table 3. To summarize this table, the length and taper of the apical spine, the width of the proxi-

| Core/section interval (in cm) | Abundance | Zone       | Preservation | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | Belemnoidops (in cm) | 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Mal shield (basal disc of spines) and the “extinction” line characteristics (interference pattern) of the proximal shield are the most important distinguishing characteristics for separating both species.

Haq (1972) first noticed the characteristic size and taper of the apical spine of S. distentus, as opposed to S. ciperoensis, using the transmission electron microscope (TEM). The length and taper of the apical spine seem good criteria for separating S. ciperoensis from S. distentus using light microscopy. However, we found many specimens with an intermediate construction. For example, Sample 101-628-21H-1, 80-81 cm, has a number of specimens with a large apical spine tapering like S. distentus, yet the “extinction” lines of the proximal shield (when the apical spine is at 45° to either polarizer) are characteristic of, or intermediate between, those of S. ciperoensis (chevronlike; Bramlette and Wilcoxon, 1967). Throughout the S. distentus–S. ciperoensis transition, most of the S. ciperoensis exhibit "extinction" lines of the proximal shield intermediate between the two species (Plate 1, Figs. 1 and 4). They also possess variable apical spine lengths, which suggests that the length of the apical spine may not be the most accurate criteria for separating these two species. These intermediate specimens probably represent transitional forms between S. distentus and S. ciperoensis. They also may represent dimorphic forms of S. ciperoensis, with the difference between the two forms being the length and taper of the apical spine.

The most accurate characteristic for separating S. ciperoensis from S. distentus in material from Hole 628A using light microscopy is the width of the proximal shield. Roth (1970) mentioned the growth of the proximal shield in the evolution from S. predistentus to S. ciperoensis, with S. ciperoensis having the widest proximal shield (basal cycle of elements). This wide proximal shield of S. ciperoensis undoubtedly is responsible for its characteristic "extinction" line pattern (chevronlike) in cross-
Table 2. Important diagnostic characteristics of *S. distentus* and *S. ciperoensis* in light and scanning electron microscopy, as described by various authors.

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<th>Zone/subzone</th>
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<td><em>S. distentus</em></td>
<td>Apical spine long, relative to <em>S. ciperoensis</em></td>
<td>Apical spine long from bifurcated tip to base.</td>
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<td></td>
<td>“Extinction” lines of proximal shield cross when apical spine is at 45° to either polarizer.</td>
<td>Apical spine short from bifurcated tip to base.</td>
</tr>
<tr>
<td></td>
<td><em>S. ciperoensis</em></td>
<td>Apical spine small with uniform taper.</td>
<td>Apical spine short with uniform taper.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>“Extinction” lines of proximal shield do not cross (chevronlike) when apical spine is at 45° to either polarizer.</td>
<td>Apical spine short with uniform taper.</td>
</tr>
</tbody>
</table>


Table 3. Diagnostic morphologic characteristics of *S. distentus* and *S. ciperoensis* (as presented in this study).

<table>
<thead>
<tr>
<th>Species</th>
<th>Diagnostic Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>S. distentus</em></td>
<td>1. Apical spine generally large; tapering gradual or not at all for proximal half, than quickly for distal half (Plate 3, Figs. 1–5).</td>
</tr>
<tr>
<td></td>
<td>2. Proximal shield rarely wider than base of apical spine (Plate 3, Figs. 1–5).</td>
</tr>
<tr>
<td></td>
<td>3. “Extinction” lines of proximal shield are “V”-shaped and cross when apical spine is at 45° to either polarizer (Plate 3, Fig. 3).</td>
</tr>
<tr>
<td><em>S. ciperoensis</em></td>
<td>1. Apical spine small, with uniform taper throughout its length (Plate 1, Figs. 7–9; Plate 2, Figs. 1–3; Plate 6, Figs. 1–4).</td>
</tr>
<tr>
<td></td>
<td>2. Proximal shield wider than any point on apical spine (Plate 1, Figs. 8 and 9; Plate 2, Figs. 2 and 3; Plate 6, Figs. 1–4).</td>
</tr>
<tr>
<td></td>
<td>3. “Extinction” lines of proximal shield are “chevronlike” and do not cross when apical spine is at 45° to either polarizer (Plate 1, Fig. 7; Plate 2, Fig. 1).</td>
</tr>
</tbody>
</table>
“extinction” line pattern (Bramlette and Wilcoxon, 1967) of the proximal shield to categorize S. ciperoensis, we were able to place most accurately the last appearance of S. distentus in relation to the foraminifer data from Hole 628A (Watkins et al., this volume). Thus, any specimen exhibiting this characteristic proximal shield “extinction” line pattern is termed S. ciperoensis regardless of the length of the apical spine.

Others also noticed this increase in width of the proximal shield, most prominently when using the electron microscope. After examination under the TEM, Roth (1970) found that the proximal shield of S. ciperoensis was much broader than the base of the apical spine (Table 2). The proximal shield of S. distentus was not distinctly wider than the base of the apical spine (Roth, 1970).

In a detailed morphologic study of selected members of the genus Sphenolithus, including S. distentus and S. ciperoensis, Roth et al. (1971b) concluded, as Roth (1970) did, that the proximal shield (basal disc) of S. distentus was equal in width or slightly wider than the base of the apical spine (Plate 2). The proximal shield (basal disc) of S. ciperoensis was significantly wider than the base of the apical spine (Roth et al., 1971b). Roth et al. also pointed out the increase in shield/body ratio from S. distentus to S. ciperoensis. In material from Hole 628A, this increase was also true, with the shield/body ratio for S. distentus at around one-fourth, transitional forms between one-third and one-fourth, and the ratio for S. ciperoensis at one-third or less.

Scanning electron micrographs of material from Hole 628A support these findings. S. distentus is characterized by a large apical spine composed of two essentially equal-sized elements (Plate 3, Figs. 1–5). The spine is wide proximally, with little or no taper for the proximal half, and then it quickly tapers distally, terminating in a fairly sharp point (Plate 3, Figs. 1–5). The proximal shield is as wide or only slightly wider than the base of the apical spine where it attaches (Plate 3, Figs. 1 and 2).

Transitional forms between S. distentus and S. ciperoensis are characterized by having a relatively large apical spine that is similar to that of S. distentus (Plate 1, Figs. 1–6; Plate 4, Figs. 3 and 4; Plate 5, Figs. 1–4). The apical spine generally has a characteristic morphology of thinness near its coupling with the proximal shield, and then it expands rapidly to its widest breadth at approximately one-third its total length. This spine then tapers quickly to a rather sharp point (Plate 4, Figs. 3 and 4; Plate 5, Figs. 1–4). The proximal shield is generally slightly larger than the base of the apical spine where it attaches and rarely much wider than the widest portion of the apical spine (Plate 4, Figs. 3 and 4; Plate 5, Figs. 1–4). Transitional forms can show wide variations in the width of the proximal shield (Plate 4, Figs. 3 and 4; Plate 5, Figs. 1–4).

Sphenolithus ciperoensis is characterized by having a relatively short, uniformly tapering apical spine consisting of two elements of equal size (Plate 1, Figs. 7–9; Plate 2, Figs. 1–3; Plate 6, Figs. 1–4). The apical spine does not possess the characteristic taper of transitional forms (Plate 6, Figs. 1–4). The proximal shield is distinctly wider than its attachment to the apical spine and any other point on the spine (Plate 6, Figs. 1–4). SEM micrographs of material from Hole 628A also clearly show the evolutionary trend in morphology to the wider proximal shield from S. predistentus to S. ciperoensis (Plate 3, Figs. 1 and 2; Plate 4, Figs. 1 and 2; Plate 6, Figs. 6–14).

When these two species were first described, the existence of forms with a bifurcating apical spine was noted (Bramlette and Wilcoxon, 1967). These were believed to represent dimorphic forms on a single living cell, as in some living coccolithophorids (Bramlette and Wilcoxon, 1967). Towe (1979) speculated that these swallowtail forms surrounded the flagellar pole of his hypothetical “sphensphere.” Although the species Towe (1979) referred to were different, his hypothesis agrees with that of Bramlette and Wilcoxon (1967). Regardless of their biological origins, these forms are not useful here because of their rarity. If these delicately branched specimens do represent dimorphs, as Towe (1979) suggested, then they would be less abundant than nonbifurcated ones, and their biostratigraphic utility would be questionable.

Alternatives to the S. ciperoensis FAD

It is clear that problems still exist when using the first evolutionary appearance of Sphenolithus ciperoensis as a biostratigraphic indicator. Because we have established the slow evolution of the S. predistentus–S. ciperoensis lineage by the presence of numerous specimens of intermediate construction between the ideal end-members, these undoubtedly will continue to cause confusion regarding taxonomy and questions about the accuracy of the S. ciperoensis FAD. In addition, the sparseness of sphenoliths in higher latitudes (Edward, 1971) makes their use difficult or impossible in these areas. When seeking possible alternatives to the sphenolith datums, we considered auxiliary nannofossil datums that we (and others) found useful in subdividing and delineating the mid- and upper-Oligocene nannofossil zones.

The LAD of Lanternithus minutus occurs at the first evolutionary appearance (FAD) of S. ciperoensis in Section 101-628A-24X, CC (Plate 2, Fig. 4; Plate 3, Figs. 6–9). Unfortunately, the LAD of this species may not be useful for approximating the FAD of S. ciperoensis for two reasons. First, and most importantly, other workers noted that L. minutus has a variable last appearance in time. Roth (1970) indicated that L. minutus becomes extinct in the lower part of the Cyclcoccolithus margaritae Zone. Roth et al. (1971a) also noted that the upper range of L. minutus extended only into the lower Oligocene at several outcrop areas in Europe. Parker et al. (1985) noted the last appearance of L. minutus only into the S. predistentus Zone of DSDP Sites 558 and 563 on the west flank of the mid-Atlantic Ridge. Bybell (1982; Fig. 7) reported L. minutus appearing beyond the FAD of S. distentus in the lower Oligocene of Alabama and Mississippi. Second, L. minutus often is not found at sites with deeper paleodepths. Okada and Thierstein (1979) did not report the occurrence of S. ciperoensis in Hole 628A, which contained a fairly thick, complete section of Oligocene. As Site 386 (DSDP Leg 43) was located in 4782 m of water, it is this water depth that could be the reason that L. minutus was not present. As the species is a holococcolith, it is particularly susceptible to dissolution. Great water depths allow a greater chance for dissolution of specimens. In addition, holococcoliths (such as L. minutus) are more susceptible to diagenetic alteration than heterococcoliths. Although Hole 628A was located in only 966 m of water, still most specimens of L. minutus show significant dissolution and/or overgrowth (Plate 3, Figs. 6–9) that make them difficult to recognize using the SEM. As a result of these two factors, the LAD of L. minutus, although occurring at the last appearance of S. ciperoensis in Hole 628A, is not necessarily useful for approximating this datum.

Only one other datum was observed to correspond to the FAD of S. ciperoensis. Helicopontosphaera compacta becomes extinct (LAD) at the first appearance of S. ciperoensis in Section 101-628A-24X, CC (Plate 2, Figs. 5 and 6; Plate 7, Figs. 2 and 4). Bramlette and Wilcoxon (1967) mentioned that this species was rare in the Globigerina opima Zone (S. distentus Zone) of the Cipero Section, and they did not show its appearance in the S. ciperoensis Zone at all. Roth (1970), however, indicated that this species ranges through his Sphenolithus distentus–S. ciperoensis zone in Alabama, Trinidad, Italy, JOIDES Holes 5 and 6, Mt. Cagnero (Italy), and the Silber Formation in Helmstedt (northern Germany). Martini (1971) also indicated
that the LAD of \textit{H. compacta} occurs in his \textit{S. ciperoensis} Zone. Haq (1972) showed that the last appearance of \textit{H. compacta} corresponds to the first appearance of \textit{S. ciperoensis} in the Oligocene of Syria, with only minor overlapping into the overlying zone. This datum helps to define the base of his \textit{Sphenolithus distinctus–S. ciperoensis} Concurrent Range Zone. The last appearance of this species seems somewhat variable, but the large size and relatively easy light-microscope identification could make the LAD of \textit{H. compacta} a good alternative marker for the beginning of the \textit{S. ciperoensis} Zone in some areas. Unfortunately, \textit{H. compacta} is found only at low abundance levels near its LAD in Hole 628A (Table 1) and, thus, may have a low level of recognition.

Another possibility is the use of alternative high-latitude datums for approximating mid-Oligocene \textit{Sphenolith} datums. Figure 2 illustrates the Oligocene nannofossil zones used by various authors in both high and low latitudes. This figure reflects the changes in floral composition and diversity between tropical and high-latitude nannofossil assemblages during the Oligocene. These changes are a result of greater latitudinal temperature gradients present during this time, which results directly from a cooling trend the whole earth experienced during the Cenozoic.

Hornbrook and Edwards (1971) used a variety of nannoplankton datums to subdivide the middle and upper Oligocene of New Zealand. Some of the datums included are \textit{Syracosphaera clathrata} (FAD), \textit{Chiasmolithus oamaruensis} (LAD), \textit{Helicopontosphaera obliqua} (FAD), and \textit{Dictyococcites bisectus} (LAD). Edwards (1971) used many of these datums to establish nannofossil zones for the New Zealand Oligocene, where a general absence of many characteristic Oligocene sphenoliths existed (Fig. 2). Martini (1981) used the last appearance of \textit{Pontosphaera enormis} to approximate the boundary between his NP24 (\textit{S. distinctus}) and NP25 (\textit{S. ciperoensis}) zones because of sparse sphenoliths. Wise (1983), like Edwards (1971), also used a variety of nannofossil datums (other than sphenoliths) to construct a zonation scheme for the Oligocene in the Falkland Plateau region because of the sparseness of diagnostic nannofossils (Fig. 2).

Most of the high-latitude mid-Oligocene datums proposed by other workers were not useful in the Bahamas. Hornbrook and Edwards (1971) provided several datums below the \textit{D. bisectus} datum for subdividing the middle Oligocene of New Zealand. From oldest to youngest these include \textit{Helicopontosphaera obliqua} (FAD), \textit{Chiasmolithus oamaruensis} (LAD), and \textit{Syracosphaera clathrata} (FAD). Neither \textit{C. oamaruensis} nor \textit{S. clathrata} were observed in the material studied. Bramlette and Wilcoxon (1967) showed that \textit{H. obliqua} first appears in the Globigerina ciperoensis ciperoensis Zone (\textit{S. ciperoensis} Zone) of Trinidad. Perch-Nielsen (1985, Fig. 42) also showed this species first appearing in the \textit{S. ciperoensis} Zone. In material from Hole 628A, \textit{H. obliqua} first appears is Section 101-628A-26X, CC, which is in the \textit{S. predistentus} Zone. As a result, it is not a good alternative to the \textit{S. ciperoensis} FAD.

Wise (1983) used the last appearances of \textit{Ericsonia fenestra} (as \textit{Clausicoccus fenestratus}), \textit{Dictyococcites bisectus}, \textit{Chiasmolithus aclites} (last common appearance), and \textit{Reticulofenestra umbilica} when he subdivided the mid-Oligocene of the Falkland Plateau region. Of these, only the last appearance of \textit{R. umbilica} was observed here (in Section 101-628A-27X, CC). Most of the mid-Oligocene alternative datums developed in higher latitudes simply cannot be applied to lower latitudes. Once again, this reflects the strong nannofossil provincialism occurring at this time because of intense latitudinal temperature gradients. This strong Oligocene provincialism created quite different nannofossil species assemblages between high and low latitudes, which makes it difficult to link useful datums between these areas.

**Other Potentially Useful Datum Levels**

A variety of other potentially useful datums were recognized from the Oligocene in Hole 628A and are given in Figure 2. These datums display varying degrees of usefulness, which depends on their consistency in occurrence, as described by various authors.

The first common appearance of \textit{Cyclicargolithus abisectus} (Sample 101-628A-25X-1, 80–81 cm) closely corresponds to the first appearance of \textit{Sphenolithus distinctus} in Sample 101-628A-25X-2, 80–81 cm. Bramlette and Wilcoxon (1967; Table 1) showed the first appearance of \textit{C. abisectus} (= \textit{Coccolithus aff. bisectus}; Bramlette and Wilcoxon, 1967) corresponding to the base of the \textit{Globigerina opima} opima Zone (\textit{S. distentus} Zone) of the Cipero Section. The FAD of \textit{C. abisectus} defined the base of the \textit{S. distentus} Zone of Roth et al. (1971a). Bukry (1973a) also stated that the first appearance of \textit{C. abisectus} could approximate the first appearance of \textit{S. distentus} at low latitudes. Although the first appearance of \textit{C. abisectus} differs from its first common appearance, the first common appearance may be more reliable as a datum because determining the FAD of this species is quite difficult owing to its slow evolution from \textit{Cyclicargolithus floridanus}. Like the slow evolution of the \textit{S. predistentus–S. ciperoensis} lineage, the slow evolution of the mid-Oligocene cyclicargoliths may inhibit their usefulness. Parker et al. (1985) noted a more irregular appearance of \textit{C. abisectus}, with this species occurring commonly in the \textit{Helicopontosphaera} Zone at DSDP Hole 558 and abundantly in this zone in DSDP Hole 563.

The last appearance of \textit{Sphenolithus pseudoradians} (Sample 101-628A-25X-2, 80–81 cm) and \textit{Discoaster tani} (Section 101-628A-25X, CC) and the first appearance of \textit{Discoaster adamanteus} (Sample 101-628A-25X-2, 80–81 cm) all correspond closely to the FAD of \textit{S. distinctus}. Bramlette and Wilcoxon (1967; Table 2) placed the last appearance of \textit{S. pseudoradians} at the base of the \textit{S. distinctus} Zone. However, Parker et al. (1985) showed \textit{S. pseudoradians} extending through the \textit{S. distinctus} Zone in DSDP Holes 558 and 563. Perch-Nielsen (1985; Fig. 67) also showed this species range extending into NP24 (CP18). Bramlette and Wilcoxon (1967; Table 2) showed the FAD of \textit{D. adamanteus} at the base of the \textit{S. distinctus} Zone. Perch-Nielsen (1985; Fig. 30) placed the first appearance of \textit{D. adamanteus} in CP18 and the last appearance of \textit{D. tani} in the underlying zone CP17. General agreement exists about the close proximity of the above datums with the FAD of \textit{S. distinctus}. Where recognized or considered, these datums might be useful for approximating the FAD of \textit{S. distinctus}. However, the thickness of the \textit{S. distinctus} Zone along with the fact that \textit{S. pseudoradians} is often found into the \textit{S. distinctus} Zone renders the possibility that some of the lower part of the \textit{S. distinctus} Zone is missing here. This missing material undoubtedly is the result of an unconformity and might cause the great number of species initiation and terminations at this point.

The last appearance of \textit{Bramletteius serraculoides} occurs within the \textit{S. predistentus} Zone in Sample 101-628A-27X-1, 80–81 cm. Few workers specifically mentioned the last appearance of \textit{B. serraculoides}. This species originally was described from the upper Coniacian of Gartner (1960) and first occurs in the middle Oligocene (Gartner, 1971). Gartner (1971) showed this species ranging into the \textit{Helicopontosphaera} Zone of the lower Oligocene but did not indicate its last appearance. Bybell (1982) showed \textit{B. serraculoides} becoming extinct in the Red Bluff and Bumpnose formations (early Oligocene) in Alabama. Parker et al. (1985) reported this species as last appearing in the \textit{R. hillae} Subzone of DSDP Hole 558 and in the lower part of the \textit{S. predistentus} Zone of DSDP Hole 563. Perch-Nielsen (1985; Fig. 19) showed this species ranging through CP16.

The last appearance of \textit{Chiasmolithus titus} occurs in Sample 101-628A-27X-2, 80–81 cm. \textit{Chiasmolithus titus} was first de-
scribed by Gartner (1970) as occurring from the middle Eocene through the upper Eocene. He noted that the species is well-developed in the Shubuta Clay Member of the Yazoo Clay (upper Eocene) in Mississippi. Bybell (1982) also showed this species ranging into the Shubuta Member, but no higher. Perch-Nielsen (1985; Fig. 19) showed the range of this species extending into CP16A. C. titus only occurs sporadically and in low abundance levels through the lower Oligocene of Hole 628A. Gartner (1970) mentioned the sporadic occurrence of this species throughout its range. Therefore, its LAD may be unrecognized and, thus, not very useful.

The LAD of the distinctive Hayella situliformis (Plate 7, Fig. 3) closely coincides with that of Ericsonia formosa in Section 101-628A-27X, CC. Where present, this extinction may help mark an upper boundary for the E. formosa Subzone (CP16b). Gartner (1971) documented the last appearance of this species in the H. reticulata Zone of JOIDES Cores J-3 and J-6B but did not mention it as a datum. Bybell (1982; Fig. 7) also reported the last appearance of H. situliformis in the lower Oligocene of Alabama and Mississippi but did not mention this as a biohorizon. Hayella situliformis is never abundant in the H. reticulata Zone of Hole 628A but is easily recognizable under the light microscope because of the high birefringence of its upper and lower rims, making it a potentially useful biostratigraphic indicator.

Both the LADs of Isthmolithus recurvus and Discoaster nodifer occur at the base of the E. formosa Subzone (CP16b; Sample 101-628A-28X-2, 80-81 cm). These datums may be useful for subdividing the lower part of the H. reticulata Zone, where the acme of E. subdisticha was not observed. Roth et al. (1970) reported that the LAD of I. recurvus occurred within their Cyclococclithus margaritae Zone. They also noted that this species became extinct near the top of their E. subdisticha Zone (CP16a; Okada and Bukry, 1980) or in the lower part of their H. reticulata Zone (CP16; Okada and Bukry, 1980). Martini (1971; Table 1) indicated that I. recurvus has its last appearance just below the top of NP22 (= top of CP16c). Bukry (1973a) reported that I. recurvus is extinct in the Ericsonia formosa Subzone (CP16b) and is present in the underlying Ericsonia subdisticha Zone (CP16a). Perch-Nielsen (1985; Fig. 78) showed this species becoming extinct in CP16c. Thus, general agreement exists that the LAD of I. recurvus is at or near the boundary of CP16b and CP16c.

Bramlette and Wilcoxon (1967) reported the last appearance of Discoaster nodifer at the base of the Globigerina opima Optima Zone (S. distentus Zone). Roth et al. (1971a) showed this species ranging into their H. reticulata Zone and, once, into the lower part of the S. predistentus Zone. Martini (1971; Table 1) indicated that D. nodifer (as D. tani nodifer) extends only into his E. subdisticha Zone. Bukry (1973b) indicated that Discoaster nodifer occurs from the upper Eocene through the S. ciperoensis Zone in the eastern equatorial Pacific. Bybell (1982; Fig. 7) also showed the range of this species extending beyond the FAD of S. distentus in Alabama and Mississippi. The LAD of D. nodifer is quite variable, and its usefulness as a biohorizon is questionable.

SUMMARY AND CONCLUSIONS

The calcareous nannofossils from Hole 628A yielded valuable information regarding Oligocene nannofossil biostratigraphy. The thickness of the S. ciperoensis Zone allowed us to examine the biostratigraphically important S. distentus–S. ciperoensis transition in detail. Initially, we thought that the length and taper of the apical spine were the most distinguishing characteristics between these two species. However, transitional forms between S. distentus and S. ciperoensis that have large apical spines like S. distentus also tend to have variable proximal shield widths. Often these shields are wide enough to produce “extinction” patterns diagnostic of S. ciperoensis when viewed in cross-polarized light. This caused confusion regarding the last appearance of S. distentus. Using light microscopy we found that the “extinction” line pattern of the proximal shield was the best characteristic for placing the FAD of S. ciperoensis and the LAD of S. distentus because it correlated most accurately with other microfossil dating. S. distentus has proximal shield “extinction” lines that are “V”-shaped and cross when the apical spine is at 45° to either polarizer (Plate 3, Fig. 3; Table 3), while in S. ciperoensis the “extinction” lines are chevronlike (Bramlette and Wilcoxon, 1967) and do not cross (Plate 1, Fig. 7; Plate 2, Fig. 1; Table 3). Any specimen that exhibits the S. ciperoensis proximal shield “extinction” lines should be considered as such regardless of the length of the apical spine.

SEM confirmed that the proximal shield “extinction” line pattern results from growth of the proximal shield during evolution from S. distentus to S. ciperoensis. Sphenolithus distentus is characterized by having a proximal shield that is only as wide, or slightly wider, than the base of the apical spine where it attaches (Plate 3, Fig. 1 and 2). S. ciperoensis has a proximal shield that is distinctly wider than the base of the apical spine or any other point on the spine (Plate 6, Figs 1-4). Transitional forms have relatively large apical spines, like S. distentus, but their proximal shields exhibit large variations in width, many of which are as wide as in S. ciperoensis (Plate 4, Figs 3 and 4, Plate 5, Figs 1-5).

The last appearances of other species, such as Lanternithus minutus and Helicopontosphaera compacta, correspond with the FAD of S. ciperoensis in Hole 628A, and we considered them as possible alternatives to it. The LAD of H. compacta may be the most useful datum for approximating the FAD of S. ciperoensis; however, some workers have noticed a somewhat variable LAD of this species, which may have a low level of recognition near its last appearance because of low abundance levels. The LAD of L. minutus is not a useful datum because of its susceptibility to dissolution at depth, its susceptibility to diagenetic alteration, and the variability of its last appearance.

Finally, transitional forms may represent an intermediate evolutionary form between S. distentus and S. ciperoensis as a result of sluggish evolution. A continuum of forms of intermediate construction between ideal end-members are to be expected in a lineage that undergoes such a gradual evolution. These transitional forms also may represent dimorphic forms on the same cell, or they simply may be the result of ontogeny overgrowth of short-spined S. ciperoensis. Even less likely, they may represent a different (biological) species. In any case, placing these intermediate forms in a well-defined category will always be difficult. However, if the criteria set forth here are adhered to, results should be better.

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REFERENCES


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APPENDIX

Calcareous Nannofossil Taxa Considered (listed alphabetically by species epithet)

- Cyclacirugolithus abjectus (Müller, 1970)
- Discoaster adamanus Breitlacker and Wilcoxon (1967)
- Chiasmolithus altus Bukry and Percival (1971)
- Scyphosphaeria apsteinii Lohmann (1902)
- Micrantholithus annotatus Breitlacker and Wilcoxon (1967)
- Verruculithus arca Bukry and Percival (1971)
- Braurosporpha bigelowii (Gan and Ibraheem, 1936) Deflandre (1947)
- Zwergusphaeria bisulca (Deflandre and Deflandre, 1954) Deflandre (1959)
- Dictyococcces bisectus (Hay, Mohler, and Wade, 1966) Bukry and Percival (1971)

- Sphenolithus ciperoensis Breitlacker and Wilcoxon (1967)
- Helicosporpha compacta Breitlacker and Wilcoxon (1967)
- Discocysta deflandrei Breitlacker and Riedel (1954)
- Braurosporpha discula Breitlacker and Riedel (1954)
- Sphenolithus distentus Martini, 1965 (Breitlacker and Wilcoxon, 1967)
- Coccocystis eopalteolus (Breitlacker and Riedel, 1954) Breitlacker and Sullivan (1961)
- Helicosporpha euraphis Haq (1966)
- Thalassopontis exilis (Breitlacker and Sullivan, 1961) Breitlacker and Nielsen (1971)
- Eriscionia superfalsata (Deflandre and Deflandre, 1954) Stradner in Stradner and Edwards (1968)
- Cyclicargolithus floridanus (Roth and Hay in Hay et al., 1967) Bukry (1971)
- Micrantholithus flos Deflandre in Deflandre and Fert (1954)
- Eriscionia formosa (Kamptner, 1963) Haq (1971)
- Thoracosphaerella fossata Jafar (1975)
- Reticulofenestra hilde Bukry and Percival (1971)
- Helicosporpha intermedi Deflandre (1965)
- Perichiazolithus joiodes Bukry and Breitlacker (1968)
- Pedinolithula larvala (Bukry and Breitlacker, 1969) Leblache and Tappan (1973)
- Lanternithus minutus Stradner (1962)
- Coccocystis microleucus Bukry (1971)
- Sphenolithus moniformis (Brönnimann and Stradner, 1960) Breitlacker and Wilcoxon (1967)
- Coronocyclus nitescens (Kamptner, 1963) Breitlacker and Wilcoxon (1967)
- Discostaurina deflandrei Breitlacker and Riedel (1954)
- Archaeocyclus obliquus Breitlacker and Wilcoxon (1967)
- Pyrolurus orangensis (Bukry, 1971) Backman (1990)
- Perna papillata Martini (1959)
- Pontosphera pectinata (Breitlacker and Sullivan, 1961)
- Sherwood (1974)
- Coccocystis pelagica (Bouggouche and Riedel, 1977) Schiller (1930)
- Helicosporpha perich-nisigenae Haq (1971)
- Hayaster perplexus (Breitlacker and Riedel, 1954) Bukry (1973)
**OLIGOCENE CALCAREOUS NANNOFOSSIL BIOSTRATIGRAPHY**

- *Sphenolithus predistentus* Bramlette and Wilcoxon (1967)
- *Calcidiscus protoannula* (Gartner, 1971) Loeblich and Tappan (1978)
- *Sphenolithus pseudoradians* Bramlette and Wilcoxon (1967)
- *Helicopontosphaera recta* Haq (1966)
- *Isthmolithus recurvus* Deflandre (1954)
- *Helicopontosphaera reticulata* Bramlette and Wilcoxon (1967)
- *Discoceras saipanensis* Bramlette and Riedel (1954)
- *Thoracosphaera saxea* Stradner (1961)
- *Dictyococites scripssae* Bukry and Percival, 1971

Plate 1. All specimens × 4125 and from Sample 101-628A-21H-1, 80-81 cm. 1-3. Transitional form between *Sphenolithus distentus* and *Sphenolithus ciperoensis*: (1) cross-polarized light, apical spine at 45° to either polarizer; (2) phase contrast; (3) transmitted light. 4-6. Transitional form; (4) cross-polarized light, apical spine at 45° to either polarizer; (5) phase contrast; (6) transmitted light. 7-9. *Sphenolithus ciperoensis*: (7) cross-polarized light, apical spine at 45° to either polarizer; (8) phase contrast; (9) transmitted light.
Plate 2. All specimens × 4125. 1-3. *Sphenolithus ciperoensis*, Sample 101-628A-21H-1, 80-81 cm; (1) cross-polarized light, apical spine at 45° to either polarizer; (2) phase contrast; (3) transmitted light. 4. *Lanternithus minutus*, cross-polarized light, Section 101-628A-25X, CC. 5-6. *Helicopontosphaera compacta*, Section 101-628A-25X, CC; (5) phase contrast; (6) transmitted light. 7-9. Species D, Sample 101-628A-24X-1, 80-81 cm; (7) cross-polarized light; (8) phase contrast; (9) transmitted light.
Plate 3. 1-2. Sphenolithus distentus, Sample 101-628A-25X-2, 80-81 cm. 3-5. Sphenolithus distentus, ×3300, Sample 101-628A-25X-2, 80-81 cm; (3) cross-polarized light, apical spine at 45° to either polarizer; (4) transmitted light; (5) phase contrast. 6. Lanternithus minutus, showing dissolution, Section 101-628A-25X, CC. 7. Same specimen as 6, ×3300, cross-polarized light. 8. Lanternithus minutus, showing dissolution, Section 101-628A-25X, CC. 9. Same specimen as 8, ×3300, cross-polarized light.
Plate 5. All specimens from Sample 101-628A-21H-1, 80-81 cm. 1, 4. Transitional form. 2. Transitional form showing slight dissolution. 3. Transitional form showing slight overgrowth.
Plate 7. 1. *Sphenolithus ciperoensis* showing slight dissolution, Sample 101-628A-21H-1, 80–81 cm. 2, 4. *Helicopontosphaera compacta*, Sample 101-628A-29X-1, 80–81 cm; (2) proximal view; (4) distal view. 3. *Hayella situiformis*, Sample 101-628A-29X-1, 80–81 cm; lateral view.