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Timothy J. Bralower; Michael A. Arthur; R. Mark Leckie; William V. Sliter; David J. Allard; Seymour O. Schlanger

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# Timing and Paleoceanography of Oceanic Dysoxia/Anoxia in the Late Barremian to Early Aptian (Early Cretaceous)

TIMOTHY J. BRALOWER

*Department of Geology, University of North Carolina, Chapel Hill, NC 27599-3315*

MICHAEL A. ARTHUR

*Department of Geosciences, Pennsylvania State University, State College, PA 16802*

R. MARK LECKIE

*Department of Geology, University of Massachusetts, Amherst, MA 01003*

WILLIAM V. SLITER

*Division of Paleontology and Stratigraphy, U.S.G.S., Menlo Park, CA 94025*

DAVID J. ALLARD

*Graduate School of Oceanography, University of Rhode Island, Narragansett, RI 02882*

SEYMOUR O. SCHLANGER*

*Department of Geological Sciences, Northwestern University, Evanston, IL 60201*

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*Normal marine deposition in the early Aptian was interrupted by an episode of ocean-wide dysoxia/anoxia. This event is recorded by the occurrence of organic carbon-rich sediments in land sections from Europe and Deep Sea Drilling Project (DSDP)/Ocean Drilling Program (ODP) sites in the North and South Atlantic, Indian and Pacific Ocean Basins. To elucidate the origin, and spatial and temporal relationships of these carbonaceous sediments, we have conducted an integrated biostratigraphic, lithostratigraphic and geochemical investigation of fourteen sections from a range of geographic and oceanographic settings. Based on the resulting high-resolution, integrated foraminiferal and nannofossil biostratigraphy, it appears that most locations were characterized by a relatively brief interval of peak dysoxia/anoxia (less than a million years in duration), in the midst of a longer (approximately 2-3 million year) interval of intermittent oxygen deficiency which began in the late Barremian. This peak can be recognized either from organic carbon contents or from intervals barren of calcareous plankton; in most places it lies within the lower Aptian* Globigerinelloides blowi *foraminiferal Zone and the* Chiastozygus litterarius *nannofossil Zone (*Conusphaera rothii *Subzone) and occurred shortly after magnetic Chron CM0. The dysoxic/anoxic interval affected sites in a wide range of oceanic paleoenvironments. Nannofossil assemblage data indicate highly variable fertility during this interval and suggest that no single model can account for the origin of all organic carbon-rich horizons. These data indicate that peak oxygen deficiency corresponded to a highly eutrophic interval but less intense dysoxic/anoxic periods were characterized by oligotrophic conditions. The late Barremian to early Aptian was a time of evolutionary radiation in both planktonic foraminifers and calcareous nannofossils, no significant changes in speciation rates are associated with the oxygen-deficient interval itself. The extinction of one of the dominant Early Cretaceous nannoplankton species,* Nannoconus steinmannii *may be related to events which led to dysoxia/anoxia including periodically higher fertility. Tectonovolcanic events such*

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* Deceased.

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*as increased production of mid-plate oceanic crust may have indirectly induced the dysoxic/anoxic episode by causing complex changes in climate, ocean chemistry and circulation, and sea level. The lack of a clear stratigraphic correlation between $C_{org}$-rich horizons and the carbon isotopic record indicates that these inter-relationships are extremely complex.*

## INTRODUCTION

Episodic events are common in Earth history. Complex interactions between climatic, oceanographic, tectonic and eustatic forcing mechanisms have been recorded in ancient marine sedimentary deposits and provide evidence of how these processes operated in the past. At certain times the rock record indicates conditions very different from those of modern oceans, which are difficult to comprehend because of the lack of an analog. Several of these fascinating, episodic events have received avid attention by stratigraphers, pertinent examples being periodic extinctions in the fossil record (e.g., Raup and Sepkoski, 1982), sedimentary cyclicity (e.g., Herbert and Fischer, 1986) and intervals in which oxygenation of oceanic deep-waters was apparently less effective (e.g., Thiede and van Andel, 1977; Waples, 1983).

For the last fifteen years, Mesozoic black shales, the products of deep-water stagnation, have been investigated in considerable detail, and from a variety of approaches. These include the sedimentology of these rocks (e.g., Arthur, 1979), their composition, both inorganic (e.g., Dean, 1981) and organic (e.g., Tissot et al., 1979), distribution (e.g., Thierstein, 1979), and origin (e.g., Schlanger and Jenkyns, 1976; Ryan and Cita, 1976). Widespread black shale deposition did not occur throughout the Mesozoic, but was concentrated in particular intervals when oceanographic and climatic conditions were appropriate. These intervals, which include the Toarcian (Early Jurassic; Jenkyns, 1980), Aptian-Albian (Early Cretaceous), Cenomanian/Turonian boundary and Coniacian-Santonian (Late Cretaceous), have been termed Oceanic Anoxic Events (OAE's) (Schlanger and Jenkyns, 1976; Arthur and Schlanger, 1979). These OAE's themselves are quite diverse. In particular, they represent highly variable durations, from less than one m.y. (Cenomanian/Turonian boundary) to over 20 m.y. (Aptian-Albian).

The most dramatic and probably the most widespread event, that at the Cenomanian/Turonian boundary, has been studied in detail in a wide variety of settings. This interval is marked by the widespread deposition of predominantly marine organic material on shelves, in epieric seaways and open ocean areas (e.g., Schlanger et al., 1987; de Graciansky et al., 1982). This is a period of dramatic turnover of macrofossil groups including ammonites (e.g., Kauffman, 1977; Cobban, 1985; Elder, 1987) and inoceramids (e.g., Elder, 1989), foraminifers (e.g., Eicher and Worstell, 1970; Leckie, 1985) and, to a lesser degree, of nannofossils (e.g., Bralower, 1988). This interval corresponds to a widespread positive excursion in the carbon isotopic composition of carbonate (e.g., Scholle and Arthur, 1980) and organic matter (e.g., Pratt and Threlkeld, 1984) which reflects both the removal of large quantities of organic material from the oceanic system and the high surface-water productivity at some localities.

Although organic carbon [$C_{org}$]-rich sediments are common in the Aptian-Albian, their spatial and temporal distribution is still not entirely clear because stratigraphic resolution is not sufficient to confidently correlate the often thin $C_{org}$-rich intervals. This is especially true for existing calcareous nannofossil zonations which contain only two zones in the Aptian stage (e.g., Thierstein, 1973; Roth, 1978; Mutterlose, 1992). Based on a detailed study of a number of sites which resulted in a higher resolution biostratigraphic scheme, Brawlower et al. (1993) concluded that the Aptian-Albian OAE as originally defined contains three widely synchronous subevents in the early Aptian, early Albian and early late Albian.

This paper summarizes the results of a detailed, integrated calcareous nannofossil biostratigraphic, lithostratigraphic, geochemical and paleoceanographic investigation of the late Barremian-early Aptian interval. $C_{org}$-rich horizons in southern France (the "Niveau Goguel" of Bréhéret (1988)), and the Southern Alps and Umbrian Apennines of Italy (the "Livello Selli" of Coccioni et al. (1987)) have previously been studied in detail and correlated (e.g., Premoli Silva et al., 1989; Weissert and Bréhéret, 1991). Sliter (1989a) correlated $C_{org}$-rich horizons in the lower Aptian *Globigerinelloides blowi* foraminiferal Zone of Pacific Deep Sea Drilling Project (DSDP) Sites 167, 305, and 463 to these $C_{org}$-rich units in Europe. Most of these previous studies were based on single sections. The approach utilized here is to include sites from a variety of different sedimentary settings from land sections and all of the major ocean basins. Because of the diversity of sections considered, biostratigraphic and lithostratigraphic correlation is not entirely straight forward and the paleoenvironmental interpretation is more complicated than previous investigations of individual sections.

## SECTIONS AND TECHNIQUES

This report is based on the investigation of 4 land and 10 DSDP/ODP sections (Fig. 1). Selection of DSDP/ODP sites was based initially on a literature survey. We have studied all sites with moderately good recovery in the Barremian/Aptian boundary interval. The lithostratigraphy and biostratigraphy of many of these sections (Table 1) has been investigated previously. Land sections are from the Umbrian Apennines (Gorgo a Cerbara, Piobbico Road) and Southern Alps (Cismon) of Italy and the Fosse Vocontien (Vergons) of France. These sequences were measured, logged, then sampled in detail, with an average of one sample every 50 cm, but up to 10 times more frequently in critical intervals. Bulk samples were taken from all different lithologies for geochemistry and nannofossil micropaleontology. Foraminiferal samples were taken simultaneously, but concentrated in limestone and harder claystone. DSDP/ODP sections have a wide geographic

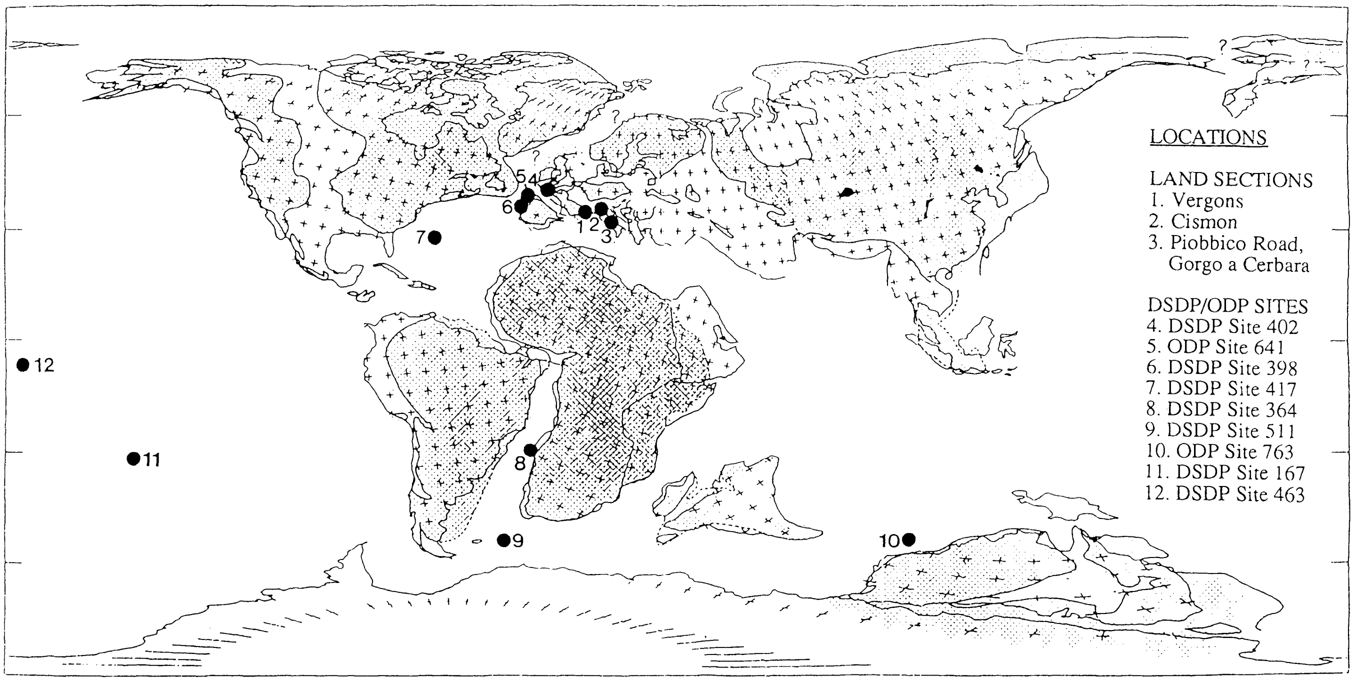


**FIGURE 1**—Map showing location of sections investigated. Shaded pattern over continents indicates land areas; unshaded pattern indicates epicontinental seaways. Reconstruction after Barron et al. (1981).

distribution, covering the eastern (DSDP Sites 398, 402 and ODP Site 641) and western (DSDP Site 417) North Atlantic, the Falkland Plateau (DSDP Site 511) and Angola Basin (DSDP Site 364) of the South Atlantic, the Equatorial Pacific (DSDP Sites 167, 305, 463) and the eastern Indian Ocean (ODP Site 763).

Nannofossil micropaleontology was carried out by Bralower on all sites and lithologies using standard smear-slide preparation techniques. The method of Monechi and Thierstein (1985) was utilized to investigate harder lithologies. The taxonomy of most species observed is standard and described in more detail by various authors (e.g., Gartner, 1968; Thierstein, 1973; Wise and Wind, 1977; Perch-Nielsen, 1985; Covington and Wise, 1987; Crux, 1989). However, there are a few problems which deserve discussion and these are dealt with in Appendix I in which a full list of the identified taxa is presented.

Thickly concentrated smear slides were prepared so that even the rarest of occurrences could be noted. Relative abundance of nannofossils was determined in the following fashion: a species was determined as abundant if, on average, more than 10 specimens could be observed in a field of view at ×1250 magnification; common if more than one specimen could be observed in each field; few if one specimen or more could be observed in every ten fields of view, and rare if, on average, one specimen could not be observed in ten fields. Preservation of nannofossils ranges from poor to good in the investigated sections and the etching and overgrowth parameters of Roth and Thierstein (1972) were used to describe the degree of alteration. Special attention was paid to samples in critical stratigraphic intervals, especially towards the ends of species ranges, where slides were examined for several hours.

Foraminiferal micropaleontology was carried out by Leckie on the Atlantic DSDP/ODP Sites and by Sliter on the Italian land sections and Pacific DSDP Sites. Leckie concentrated mostly on marlstones and claystones which could be washed using standard techniques, and Sliter worked predominantly on limestones using thin sections. The two workers collaborated closely and exchanged samples in critical intervals. Detailed foraminiferal taxonomy and stratigraphic distributions will be presented elsewhere (Leckie and Sliter, in prep.).

In this report, we interpret $C_{org}$ and carbonate data taken from the literature and analyzed at GSO/URI and at UNC-CH using Coulometrics coulometers (Fig. 2). Various other geochemical analyses, including Rockeval pyrolysis and measurement of stable carbon and oxygen isotopes on carbonates and carbon isotopes of bulk $C_{org}$ were also carried out. The results of these investigations are documented and discussed in detail in Allard et al. (in prep.).

## BIOSTRATIGRAPHY OF THE LATE BARREMIAN-EARLY APTIAN

### Calcareous Nannofossils

Previous calcareous nannofossil biostratigraphies for the late Barremian-early Aptian interval lack resolution required for interpretation of fine-scale paleoceanographic events. However, this is an interval with a rapid turnover

**TABLE 1**—Sources of lithological, biostratigraphical and magnetostratigraphical data in sections investigated.

| Section | Lithostratigraphy | Biostratigraphy | Magnetostratigraphy | Carbon/Carbonate |
|---|---|---|---|---|
| DSDP 167 | Winterer et al., 1973 | Roth, 1973 (n); Douglas, 1973 (f); Tarduno et al., 1989 (n, f) | Tarduno et al., 1989 | — |
| DSDP 364 | Bolli et al., 1978 | Proto Decima et al., 1978 (n); Caron, 1978 (f) | — | Foresman, 1978; this study |
| DSDP 398 | Arthur, 1979; Sibuet et al., 1979 | Blechschmidt, 1979 (n); Sigal, 1979 (f) | — | Sibuet et al., 1979; Erdman and Schorno, 1979; Johnson et al., 1979 |
| DSDP 402 | Montadert, Roberts et al., 1979 | Müller, 1979 (n) | Tarduno, 1990 | Deroo et al., 1979; this study |
| DSDP 417 | Donnelly et al., 1980 | Gartner, 1980 (n); Siesser, 1980 (n) | — | Deroo et al., 1980; this study |
| DSDP 463 | Dean et al., 1981 | Cepek, 1981 (n); Roth, 1981 (n); Tarduno et al., 1989 (n, f) | Tarduno et al., 1989 | Dean et al., 1981; this study |
| DSDP 511 | Ludwig et al., 1983 | Krashenninikov and Basov, 1983 (f); Wise, 1983 (n) | Salloway, 1983 | Deroo et al., 1983; Bode, 1983; Parker et al., 1983, this study |
| ODP 641 | Boillot et al., 1988 | Applegate and Bergen, 1988 (n) | Ogg, 1988 | Boillot et al., 1988; this study |
| ODP 763 | Haq et al., 1990 | Bralower and Siesser, 1992 (n) | — | this study |
| Vergons | — | — | — | this study |
| Cismon | — | Channell et al., 1979 (n, f); Bralower, 1987 (n) | Channell et al., 1979 | this study |
| Piobbico | — | — | — | this study |
| Cerbara | Coccioni et al., 1989 | Lowrie et al., 1980 (n, f); Bralower, 1987 (n) | Lowrie and Alvarez, 1984 | — |

n = nannofossils; f = foraminifera.

of nannofossil taxa (Roth, 1987) and therefore the potential exists for improved biostratigraphic resolution. Most zonations contain the *Watznaueria oblonga* Zone (NC5) in the late Barremian and the *Chiastozygus litterarius* Zone (NC6) in the early Aptian (Fig. 3). The boundary between these two zones can be defined by two different events. These are the first occurrences (FO's) of *Chiastozygus litterarius* (e.g., Thierstein, 1973; Sissingh, 1977; Roth, 1978, 1983; Wiegand, 1984; Bralower, 1987) and *Rucinolithus irregularis* (e.g., Erba and Quadrio, 1987; Applegate and Bergen, 1988). The top of this zone is usually defined by the FO of *Parhabdolithus angustus* (e.g., Manivit, 1971; Roth, 1978), but the FO of *Eprolithus floralis* has been suggested as an alternative (e.g., Thierstein, 1973; Wiegand, 1984; Erba, 1988). Some studies indicate that the FO's of *E. floralis* and *P. angustus* coincide (e.g., Thierstein, 1973; Roth, 1983; Erba, 1988), whereas others suggest either that the FO of *E. floralis* precedes (e.g., Applegate and Bergen, 1988) or postdates (e.g., Mutterlose, 1989) that of *P. angustus*. We have carried out a detailed taxonomic study of *P. angustus* and on this basis have emended the definition of this species (see Appendix I). Based on the new definition, we find that the first occurrence of *P. angustus* lies considerably below that of *E. floralis* and slightly below the first occurrence of *R. irregularis*.

With the exception of the zonal markers, there is little agreement as to the stratigraphic order of the numerous subsidiary events which occur in this interval. For example, some studies indicate that the last occurrence (LO) of *N. steinmannii* was in the late Barremian (e.g., Bralower, 1987), while others find that it was in the early Aptian (e.g., Erba, 1988). There are numerous other species which evolved in the late Barremian-early Aptian interval. These include *Corollithion achylosum, C. acutum, Flabellites oblongus, Grantarhabdus coronadventis* and *Axopodorhabdus decorus.* Additional taxa disappeared in this interval, including *Cretarhabdus angustiforatus* (see Appendix I for taxonomic clarification), *Conusphaera rothii* (*C. mexicana* subsp. *mexicana*) and *Hayesites radiatus.* One of the major objectives of this investigation is to see whether these events can be ordered in a consistent fashion in multiple sites and therefore be applied in a higher resolution biostratigraphy for the late Barremian-early Aptian interval.

Meter levels of potentially useful nannofossil events in the Barremian/Aptian boundary interval are presented in Table 2. All of these events can be determined in the

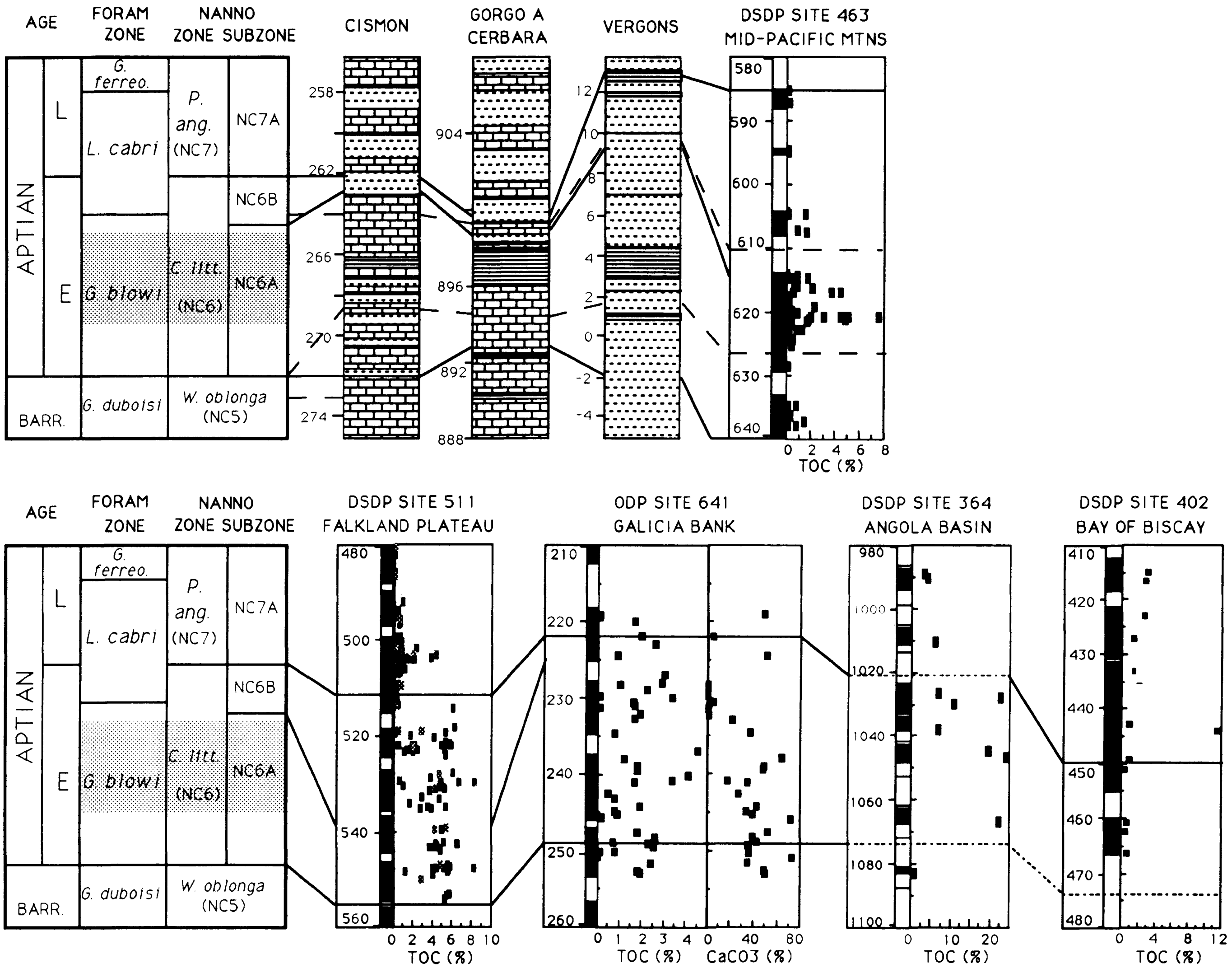


**FIGURE 2**—Correlation of organic carbon-rich horizons in the early Aptian interval. Diagram shows recovery and generalized lithostratigraphy, and in the DSDP/ODP sites $C_{org}$ and $CaCO_3$ contents, for sections investigated and correlation with planktonic foraminiferal and calcareous nannofossil events and with magnetic polarity zone M0. Scale of sections shown: long, wide tick-marks—20 m; short, wide marks—10 m; long, narrow marks—2 m. Dashed correlation lines indicate uncertain ties.

expanded, continuous sections at DSDP Site 398 and ODP Site 641. The other sections, including DSDP Sites 167, 364, 402, 417, 463, and 511, ODP Site 763 and the land sections, are characterized by various problems including poorer microfossil preservation and sediment recovery, but provide important biostratigraphic information in certain intervals. Because of the extremely poor recovery, we have omitted DSDP Site 305 from further analysis. Range charts from the other sections are illustrated in detail in Figures 4 to 16. In the following, we discuss the biostratigraphic potential of twelve biohorizons in this interval.

All but three of the twelve biohorizons can be determined precisely in ODP Hole 641C (Fig. 4A, B). These three events include the FO's of *Axopodorhabdus decorus* and *Grantarhabdus coronadventis,* species which display transitional evolutionary connections with *Hemipodorhabdus gorkae* and *Grantarhabdus meddii,* respectively (see Appendix I for details), and the LO of *Micrantholithus hoschulzii* which has an extremely patchy distribution up into the Albian of this hole. There is some uncertainty related to the determination of three other events in Hole 641C. These include the FO of *Chiastozygus litterarius* which is found in the Hauterivian of this hole (Applegate and Bergen, 1988; see Appendix I), but reappears in Section 641C-11R-1 in the upper Barremian. The species *Corollithion achylosum* has a very patchy distribution in the lowermost part of its range (Fig. 4), and there is some uncertainty related to the determination of the FO of *Parhabdolithus angustus* (see Appendix I for discussion). Previous biostratigraphic investigation of Hole

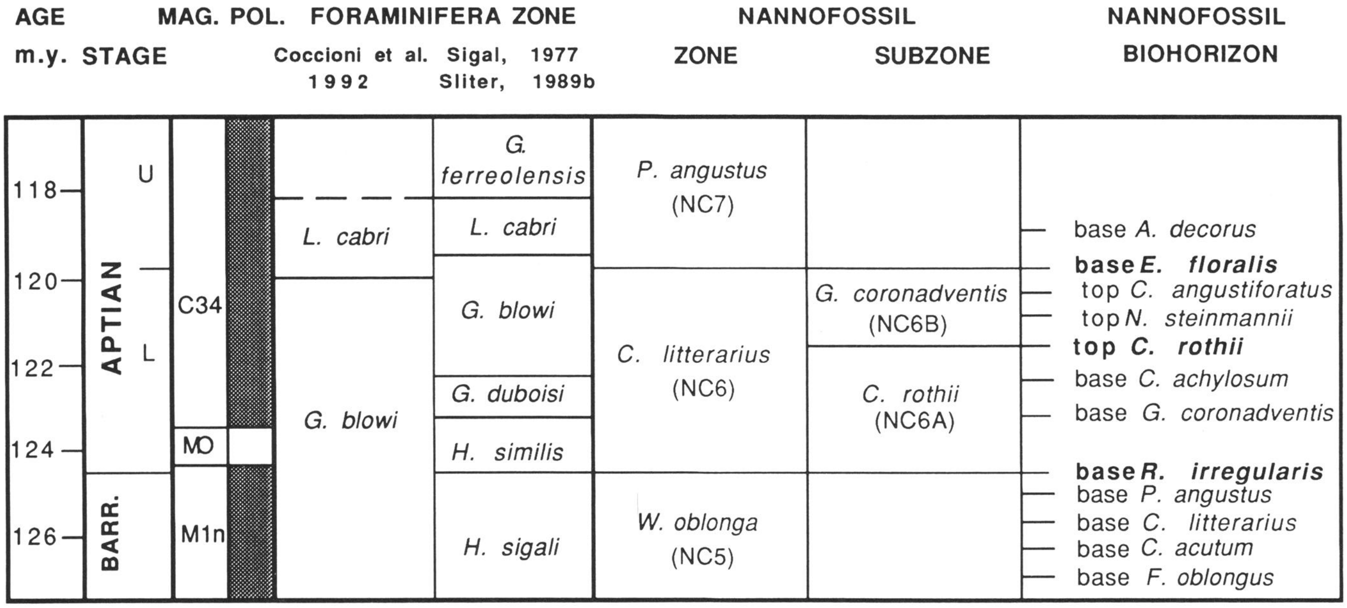


**FIGURE 3**—Proposed calcareous nannofossil zonation for the Barremian/Aptian boundary interval and correlation with planktonic foraminiferal zonation. Two different foraminiferal chronostratigraphic schemes are presented: a. Coccioni et al. (1992) and b. Sigal (1977) and Sliter (1989b).

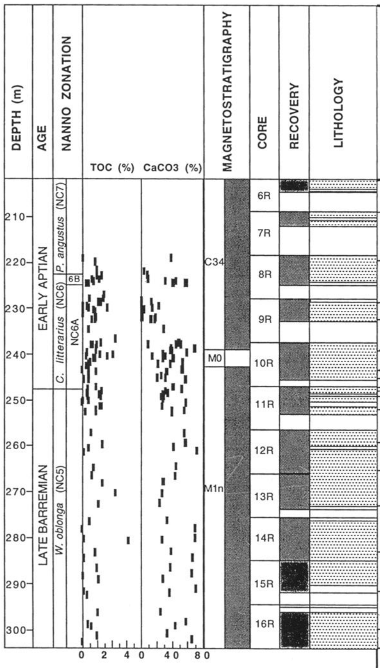
**TABLE 2**—Meter levels of events in sections investigated.

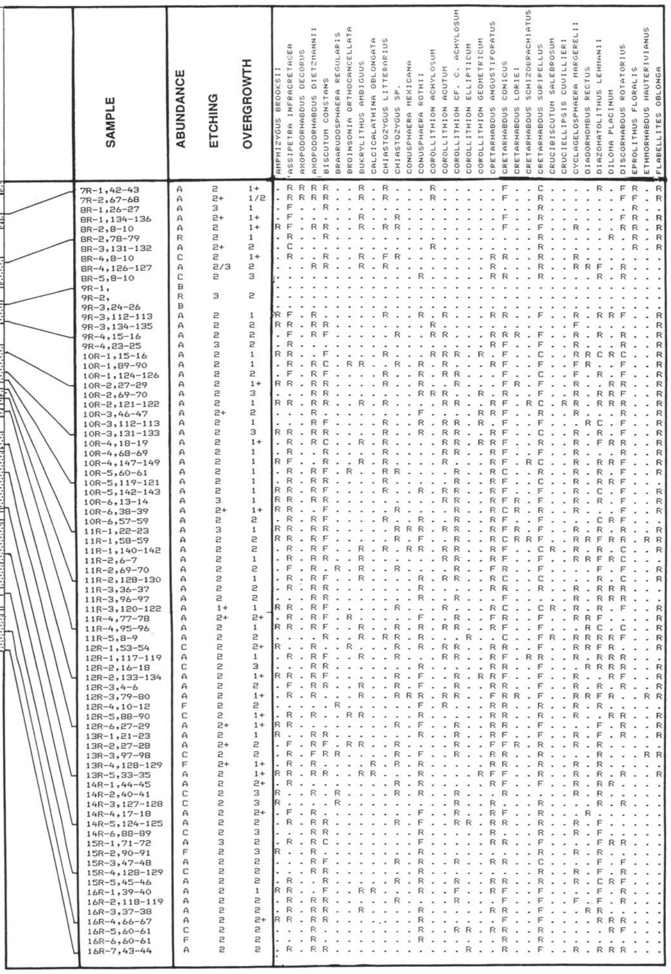
| Event | 641C | 398D | 511 | 417D | 167 | 463 | 763B | VER | CIS | PIO | CER | 364 | 402A |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Base *A. decorus* | 210.9 | 1517.6 | — | Base | — | — | 560.5 | — | — | — | — | — | — |
| Base *E. floralis* | 222.7 | 1551.5 | 510.9 | 337.6 | 895.1 | 604.5 | 560.5 | — | 262.1 | 322.5 | 899.5 | — | 445.7 |
| Top *C. angustiforatus* | 223.1 | 1563.6 | — | — | 909.6 | — | — | 12.8 | — | — | - | — | — |
| Top *N. steinmannii* | 223.1 | Top | — | — | — | — | — | - | Top | 311.0 | 884.0 | — | — |
| Top *C. rothii/C. mex.* | 224.6 | 1568.5 | 538.1 | — | — | 613.9 | — | 12.8 | 263.2 | 318.3 | 898.0 | — | 451.1 |
| Base *C. achylosum* | 237.8 | 1565.5 | 511.1 | Base | — | — | — | — | — | — | — | 1036.1 | — |
| Base *G. coronadventis* | 240.3 | 1591.2 | 550.6 | Base | — | — | 560.5 | — | — | — | — | 1036.1 | — |
| Base *R. irregularis* | 248.7 | 1595.0 | — | Base | 909.6 | Base | — | 1.3 | 271.0 | 308.3 | 893.1 | 1036.1 | Base |
| Base *P. angustus* | 250.1 | 1601.2 | 511.6 | 325.3 | — | — | 560.5 | — | 250.5 | — | 903.0 | — | — |
| Base *C. litterarius* | 253.4 | 1642.3 | — | — | — | — | 560.8 | — | — | — | 893.1 | — | — |
| Base *C. acutum* | 261.5 | 1617.6 | — | Base | — | — | — | — | — | — | — | — | — |
| Base *F. oblongus* | 272.8 | 1640.9 | — | Base | 909.6 | Base | — | — | — | — | — | 1037.1 | — |

Base indicates event level lies below base of section. Top indicates event level lies above top of section. — indicates event cannot be determined in that section. VER = Vergons; CIS = Cismon; PIO = Piobbico; CER = Gorgo a Cerbara.

641C by Applegate and Bergen (1988) produced very similar results for the major markers, including the first occurrences of *Rucinolithus irregularis* and *Eprolithus floralis,* but these authors did not concentrate on the subsidiary biohorizons in this interval. The magnetostratigraphic investigation of this hole by Ogg (1988) indicates polarity zone M-O lies in the middle part of Core 641C-10R which is in the lower part of the *Chiastozygus litterarius* nannofossil Zone, in a similar position to the results of Tarduno et al. (1989), Channell and Erba (1992) and Coccioni et al. (1992).

The majority of these same events could be determined in Hole 398D (Fig. 5A, B; Table 2). In addition, early occurrences of *Axopodorhabdus decorus* and *Grantarhabdus coronadventis* were less transitional in this site, although these markers were rarer than in Hole 641C. As in Hole 641C, numerous specimens of *Chiastozygus* similar to *C. litterarius* were observed below the Aptian. The FO of *P. angustus* (emended definition) was found to precede that of *Rucinolithus irregularis.* Reworking is pervasive at this site, with numerous specimens of *Cruciellipsis cuvillieri, Calcicalathina oblongata* and *Speetonia colligata* observed far above their normal extinction levels in the upper Hauterivian and lower Barremian. This reworking has probably extended the ranges of *Nannoconus stein-*





**LITHOLOGY**

▨ CLAYSTONE/MARLSTONE
▤ DARK SHALE
▦ LIMESTONE/CHALK
▒ SILTSTONE/SANDSTONE

**RELATIVE ABUNDANCE**

R = Rare
F = Few
C = Common
A = Abundant
? = Questionably Present
• = Not Present

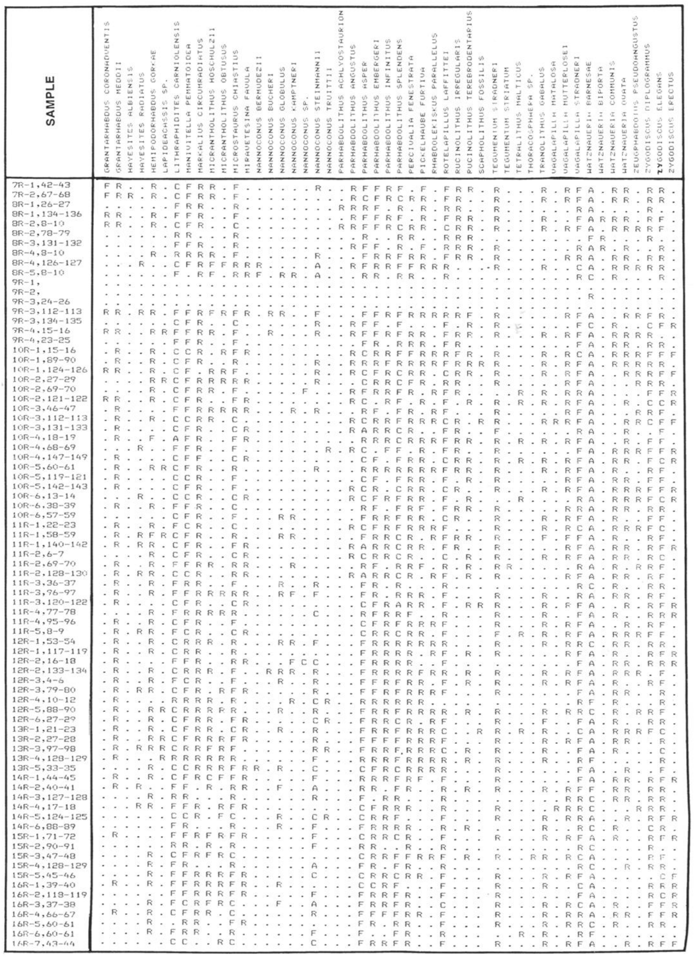
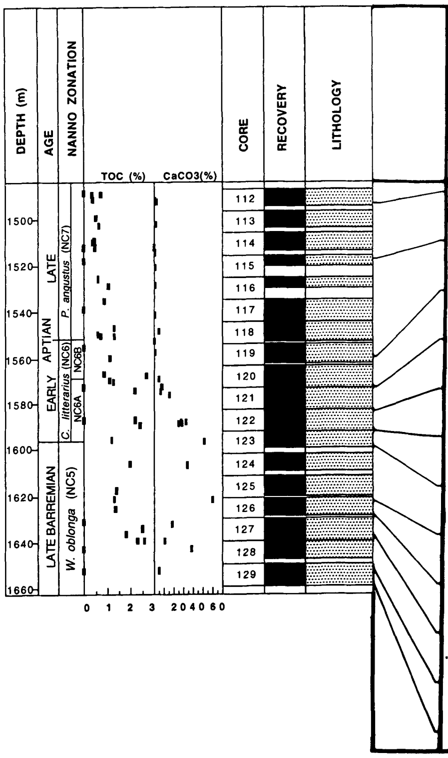


**FIGURE 4A**—Range chart of calcareous nannofossils in ODP Hole 641C. Nannofossil zonation is shown at left. Magnetostratigraphy is after Ogg (1988). Organic carbon and carbonate data are taken from the literature (Table 1) and obtained as part of this study. Recovery shows gaps in section in white. See key for explanation of lithologic and biostratigraphic symbols.

**FIGURE 4B**—Range chart of calcareous nannofossils in ODP Hole 641C. See Figure 4A for complete explanation.



| SAMPLE | ABUNDANCE | ETCHING | OVERGROWTH | AMPHIZYGUS BROOKSII | ASSIPETRA INFRACRETACEA | AXOPODORHABDUS DECORUS | AXOPODORHABDUS DIETZMANNII | BISCUTUM CONSTANS | BRAARUDOSPHAERA REGULARIS | BUKRYLITHUS AMBIGUUS | CALCICALATHINA OBLONGATA | CHIASTOZYGUS LITTERARIUS | CHIASTOZYGUS SP. | CONUSPHAERA MEXICANA | CONUSPHAERA ROTHII | COROLLITHION ACHYLOSUM | COROLLITHION ACUTUM | COROLLITHION CF. C. ACHYLOSUM | COROLLITHION ELLIPTICUM | COROLLITHION GEOMETRICUM | CRETARHABDUS ANGUSTIFORATUS | CRETARHABDUS CONICUS | CRETARHABDUS LORIEI | CRETARHABDUS SCHIZOBRACHIATUS | CRETARHABDUS SURIRELLUS | CRUCIBISCUTUM SALEBROSUM | CRUCIELLIPSIS CUVILLIERI | CYCLAGELOSPHAERA DEFLANDREI | CYCLAGELOSPHAERA MARGERELII | DIADORHOMBUS RECTUS | DIAZOMATOLITHUS LEHMANII | DILOMA PLACINUM | DISCORHABDUS ROTATORIUS | EPROLITHUS FLORALIS | ETHMORHABDUS GALLICUS | ETHMORHABDUS HAUTERIVIANUS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 112-5,49-50 | A | 2 | 2 | R | R | . | . | R | . | R | . | R | . | . | . | R | . | . | . | . | . | R | . | . | F | . | . | . | . | . | . | . | . | R | . | . |
| 113-2,20-21 | A | 2 | 1 | . | . | . | . | . | R | . | R | . | . | . | . | . | . | . | . | R | . | . | . | . | . | . | R | . | . | . | . | . | . | . | . | . |
| 113-3,90-01 | A | 2 | 1 | . | R | R | . | . | . | . | . | R | . | . | . | R | . | . | . | . | . | F | . | R | F | . | R | . | F | . | R | . | . | R | . | . |
| 114-2,34-35 | A | 2 | 1 | . | . | . | R | R | R | R | . | R | . | . | . | R | . | . | . | . | . | F | . | . | R | . | . | . | . | . | . | . | . | R | . | . |
| 114-4,91-93 | C | 3 | 2 | . | . | R | . | . | R | . | . | R | . | . | . | . | . | . | . | . | . | R | . | . | R | . | R | . | . | . | R | . | . | R | . | . |
| 115-2,59-60 | A | 2 | 1 | . | R | R | R | R | . | R | . | R | . | . | . | R | . | . | . | . | . | F | . | . | R | . | . | . | R | . | R | . | R | . | . | . |
| 117-1,119-121 | C | 2 | 2 | . | . | . | R | R | . | . | . | R | . | . | . | . | . | . | . | . | . | F | . | . | R | . | R | . | . | . | R | . | R | . | . | . |
| 117-5,80-82 | A | 2 | 1 | . | R | . | R | F | R | R | R | R | R | . | . | . | . | R | . | . | . | F | . | . | F | . | . | . | F | . | R | . | F | R | . | . |
| 118-1,44-46 | A | 3 | 2 | . | F | . | R | R | . | . | . | . | . | . | . | . | . | . | . | . | . | F | R | . | R | . | . | . | . | . | R | . | R | R | . | . |
| 118-5,147-147 | F | 3 | 2 | . | R | . | R | R | . | . | . | . | . | . | . | . | . | . | . | . | . | R | . | . | R | . | . | . | R | . | R | . | . | R | . | . |
| 119-4,42-44 | F | 2 | 2 | . | R | . | . | . | . | . | R | . | . | . | . | . | . | . | . | . | . | . | . | . | R | . | . | . | . | . | R | . | . | . | . | . |
| 120-1,63-64 | A | 2 | 2 | . | R | . | R | R | . | . | . | . | R | . | . | . | R | . | . | . | R | F | . | . | F | . | . | . | F | R | . | R | R | . | . | . |
| 120-2,100-102 | C | 2 | 1 | . | . | . | . | . | . | . | . | . | . | . | . | R | . | . | . | . | R | R | . | . | R | . | . | . | R | . | . | . | . | . | . | . |
| 120-3,58-59 | A | 3 | 1 | . | R | . | . | R | . | . | . | . | . | . | . | . | . | . | . | . | R | R | . | . | F | . | . | . | . | . | . | . | . | . | . | . |
| 120-4,103-105 | A | 2 | 1 | . | R | . | . | R | . | . | . | . | . | . | R | . | R | . | . | . | R | R | . | R | R | . | . | . | F | R | R | R | R | . | . | . |
| 120-6,134-136 | C | 2 | 1 | . | R | . | R | . | R | . | . | R | . | . | . | . | R | R | . | . | R | F | R | . | R | . | R | . | R | . | R | R | . | . | . | . |
| 121-1,24-25 | A | 2 | 1 | . | . | . | R | R | . | R | . | R | . | . | . | . | R | . | . | . | . | R | . | . | R | . | R | . | F | . | R | R | . | . | . | . |
| 121-3,58-59 | A | 2 | 1 | . | . | . | R | . | . | . | . | R | . | . | R | . | R | R | . | . | . | F | . | . | F | . | . | . | R | . | R | R | R | . | . | . |
| 121-4,30-31 | C | 2 | 1 | . | R | . | . | . | . | . | . | R | . | . | . | . | . | . | . | . | R | F | . | . | F | . | . | . | R | . | R | . | . | . | . | . |
| 121-6,138-142 | A | 2 | 2 | . | R | . | . | . | . | R | . | R | . | . | . | . | R | . | . | . | R | F | . | . | C | . | . | . | F | . | . | R | R | . | . | . |
| 122-1,67-69 | C | 3 | 2 | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | F | . | . | F | . | . | . | R | . | . | . | . | . | . | . |
| 122-2,131-133 | A | 3 | 2 | . | R | . | . | R | . | . | . | . | . | . | . | . | . | . | . | . | R | F | . | . | R | . | . | . | F | . | R | . | R | . | . | . |
| 122-3,41-42 | A | 2 | 1 | . | R | . | . | . | . | . | . | R | . | . | R | . | R | R | . | . | R | F | R | . | F | . | . | . | R | . | . | . | . | . | . | . |
| 122-4,100-102 | A | 2 | 2 | . | R | . | R | R | . | . | . | . | . | . | R | . | . | . | . | . | . | R | . | . | F | . | . | . | F | . | R | R | . | . | . | . |
| 122-6,33-34 | C | 2 | 1 | . | R | . | R | R | . | . | . | . | . | R | R | . | . | R | . | . | R | R | . | . | R | . | . | . | . | . | R | R | R | . | . | . |
| 122-7,23-24 | A | 2 | 1 | . | R | . | . | F | . | . | . | R | . | . | R | . | R | . | . | . | R | R | . | . | F | . | . | . | F | . | R | . | R | . | . | . |
| 123-1,49-50 | A | 2 | 1 | . | R | . | R | R | . | . | . | . | . | . | . | . | R | . | . | . | R | F | . | . | F | . | . | . | F | . | . | R | R | . | . | . |
| 123-2,35-36 | A | 2 | 2 | . | R | . | . | . | . | . | . | R | . | . | . | . | . | . | . | . | R | R | . | . | R | . | . | . | C | . | . | . | . | . | . | . |
| 123-3,48-49 | A | 2 | 1 | . | R | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | F | . | . | R | . | . | . | F | . | . | . | . | . | . | . |
| 123-4,96-97 | F | 3 | 2 | . | R | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | . | R | . | . | R | . | . | . | . | . | . | . | . | . | . | . |
| 123-5,39-40 | A | 2 | 2 | . | R | . | . | R | . | . | . | . | R | . | R | . | . | R | . | . | . | . | . | . | R | R | . | . | F | . | R | R | F | . | . | . |
| 124-1,17-18 | A | 2 | 2 | . | R | . | R | R | . | . | R | . | R | . | R | . | . | R | . | . | R | R | . | . | R | . | . | . | F | . | R | R | . | . | . | . |
| 124-4,45-47 | A | 2 | 1 | . | . | . | R | F | . | R | R | . | . | R | R | . | . | R | . | . | . | . | . | . | R | . | . | . | F | . | R | . | F | . | . | . |
| 125-6,64-65 | C | 2 | 1 | R | R | . | R | R | . | . | . | . | . | . | . | . | R | R | . | . | R | F | . | . | F | . | . | . | F | . | R | R | R | . | . | . |
| 125-5,113-115 | A | 2 | 1 | . | R | . | R | R | . | R | R | R | . | . | F | . | R | R | . | . | R | R | . | . | F | . | . | . | R | . | R | R | R | . | . | R |
| 126-1,120-122 | A | 2 | 1 | . | . | . | R | R | . | . | . | . | . | . | R | . | . | R | . | . | R | R | . | . | F | R | . | . | . | . | F | R | F | . | . | . |
| 126-2,43-44 | A | 2 | 1 | . | R | . | R | R | . | . | . | R | R | . | R | . | . | R | . | . | R | . | . | . | R | . | . | . | F | . | R | . | F | . | . | . |
| 126-3,110-113 | A | 2 | 1 | . | R | . | . | . | . | . | . | R | . | . | R | . | . | R | . | . | R | F | . | . | R | . | . | . | R | . | R | R | . | . | . | . |
| 126-4,57-58 | A | 2 | 1 | . | R | . | R | R | . | R | . | . | . | . | . | . | . | . | . | . | R | F | R | . | R | R | . | . | F | . | . | . | F | . | . | . |
| 126-5,113-115 | C | 2 | 2 | . | . | . | R | R | . | R | . | . | . | R | . | . | . | . | R | . | . | R | . | . | F | . | . | . | F | . | R | . | R | . | . | . |
| 126-6,37-38 | C | 2 | 2 | R | R | . | R | . | . | R | . | . | R | . | R | . | . | . | . | . | R | F | . | . | R | . | . | . | R | R | R | . | . | . | . | . |
| 127-1,20-21 | C | 1 | 1 | . | . | . | R | F | . | . | R | R | . | R | R | . | . | R | . | . | R | F | R | . | F | R | R | . | R | R | R | R | R | . | . | . |
| 127-2,53-55 | C | 2 | 2 | R | . | . | R | . | R | . | R | . | . | . | . | . | . | R | . | . | R | R | . | . | R | R | R | . | F | . | R | . | . | . | . | . |
| 127-3,102-104 | A | 2 | 2 | . | . | . | R | . | . | . | . | . | . | . | R | . | . | R | . | . | R | R | . | . | R | . | R | . | R | . | R | R | . | . | . | . |
| 127-4,45-46 | A | 2 | 1 | R | . | . | R | . | R | . | . | . | . | . | R | . | . | R | . | . | R | F | . | . | R | R | . | . | R | . | . | R | . | . | . | . |
| 127-5,25-26 | A | 2 | 1 | . | R | . | . | . | R | R | R | R | R | R | R | . | . | R | . | . | R | F | . | . | R | . | . | . | R | . | R | . | . | . | . | . |
| 127-6,64-65 | C | 2 | 1 | . | R | . | R | . | . | . | . | . | . | R | . | . | . | . | . | . | R | F | R | . | R | . | R | . | . | . | R | . | . | . | . | . |
| 128-1,40-41 | A | 2 | 1 | R | R | . | R | F | . | R | . | R | R | . | R | . | . | R | . | . | R | R | R | . | R | R | R | . | R | . | R | R | R | . | . | R |
| 128-2,35-36 | C | 2 | 1 | . | R | . | R | R | . | R | . | . | . | . | . | . | . | R | . | . | R | F | . | . | R | R | R | R | F | . | F | R | . | . | . | . |
| 128-3,32-33 | A | 2 | 1 | . | R | . | R | . | . | R | . | R | . | . | . | . | . | R | . | . | R | F | . | . | R | . | . | . | . | . | . | R | R | . | . | . |
| 129-1,125-127 | A | 1 | 1 | . | R | . | R | R | . | R | R | . | R | . | . | . | . | R | . | . | R | F | R | . | R | R | . | . | R | . | R | R | F | . | R | . |
| 129-2,44-45 | A | 2 | 1 | R | R | . | R | . | . | . | R | . | . | R | R | . | . | . | . | . | F | C | . | . | F | . | R | . | R | . | R | . | R | . | . | . |
| 129-3,126-128 | C | 3 | 2 | . | . | . | . | . | . | . | R | . | R | . | . | . | . | . | . | . | R | R | . | . | R | . | R | . | R | . | R | . | . | . | . | . |
| 129-4,61-62 | A | 2 | 1 | R | . | . | R | . | . | . | . | . | . | . | R | . | . | . | . | . | . | R | . | . | F | . | . | . | F | . | R | R | R | . | . | . |
| 129-5,119-121 | A | 2 | 2 | . | R | . | R | R | . | R | R | . | R | . | R | . | . | . | . | . | R | F | . | . | R | . | R | . | R | R | R | . | . | . | . | . |
| 129-6,42-43 | A | 3 | 2 | . | R | . | R | . | . | . | . | . | . | . | R | . | . | . | . | . | R | R | . | . | R | . | . | . | R | . | R | R | . | . | . | . |
| 129-7,9-10 | A | 2 | 2 | . | R | . | R | . | . | . | R | . | R | . | R | . | . | . | . | . | R | F | . | . | R | . | . | . | R | R | . | R | . | . | . | . |

| SAMPLE | FLABELLITES OBLONGUS | GRANTARHABDUS CORONADVENTIS | GRANTARHABDUS MEDDII | HEMIPODORHABDUS GORKAE | LAPIDEACASSIS SP. | LITHRAPHIDITES ALATUS MAGNUS | LITHRAPHIDITES CARNIOLENSIS | MANIVITELLA PEMMATOIDEA | MARKALIUS CIRCUMRADIATUS | MICRANTHOLITHUS OBTUSUS | MICRANTHOLITHUS HOSCHULZII | MICROSTAURUS CHIASTIUS | MIRAVETESINA FAVULA | NANNOCONUS BERMUDEZII | NANNOCONUS BUCHERI | NANNOCONUS GLOBULUS | NANNOCONUS KAMPTNERI | NANNOCONUS SP. | NANNOCONUS STEINMANNII | NANNOCONUS TRUITTII | PARHABDOLITHUS ANGUSTUS | PARHABDOLITHUS ASPER | PARHABDOLITHUS EMBERGERI | PARHABDOLITHUS INFINITUS | PARHABDOLITHUS SPLENDENS | PERCIVALIA FENESTRATA | PICKELHAUBE FURTIVA | RHABDOLEKISKUS PARALLELUS | ROTELAPILLUS LAFFITTEI | RUCINOLITHUS IRREGULARIS | RUCINOLITHUS TEREBRODENTARIUS | SCAPHOLITHUS FOSSILIS | SOLLASITES HORTICUS | SPEETONIA COLLIGATA | TEGUMENTUM STRADNERI | TETRALITHUS MALTICUS | THORACOSPHAERA SP. | TRANOLITHUS GABALUS | VAGALAPILLA MUTTERLOSEI | VAGALAPILLA STRADNERI | WATZNAUERIA BARNESAE | WATZNAUERIA BIPORTA | WATZNAUERIA COMMUNIS | WATZNAUERIA OVATA | ZEBRASHAPKA SP. | ZEUGRHABDOTUS PSEUDANGUSTUS | ZYGODISCUS DIPLOGRAMMUS | ZYGODISCUS ELEGANS | ZYGODISCUS ERECTUS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 112-5,49-50 | . | . | . | . | . | . | F | R | . | . | R | . | . | . | . | . | . | . | R | . | . | R | R | . | F | . | R | . | R | . | R | . | . | . | R | . | . | . | . | R | C | R | . | . | . | . | R | F | . |
| 113-2,20-21 | . | . | R | . | . | . | . | . | . | . | . | . | . | . | . | . | . | F | R | R | . | . | . | . | . | . | . | R | . | . | . | . | . | . | . | . | R | . | . | . | A | . | . | R | . | . | R | R | . |
| 113-3,90-01 | R | . | R | . | . | . | F | F | . | R | R | R | . | . | . | . | . | . | R | . | . | R | R | R | F | R | R | . | R | . | R | . | . | . | R | . | . | . | R | F | A | . | R | . | . | . | R | F | . |
| 114-2,34-35 | R | . | . | . | . | . | F | F | R | . | R | R | . | . | . | R | R | F | R | . | R | R | R | . | F | R | R | . | R | . | . | . | . | . | . | . | . | . | R | . | A | . | R | R | . | . | R | R | . |
| 114-4,91-93 | R | R | . | . | . | . | F | . | . | . | . | . | . | . | . | . | . | F | . | . | R | R | R | . | F | R | . | . | R | . | R | . | . | . | R | . | . | . | R | F | C | . | R | R | . | . | R | F | . |
| 115-2,59-60 | . | R | R | . | . | . | F | F | . | . | R | R | . | . | . | . | . | F | R | . | R | R | R | F | . | R | R | . | R | . | . | . | . | R | R | . | . | . | R | F | A | . | . | R | . | . | R | F | . |
| 117-1,119-121 | . | . | . | . | . | . | F | . | . | . | R | R | . | . | . | . | . | R | R | . | R | R | . | . | F | R | R | R | R | . | . | . | . | . | R | . | . | . | . | R | C | . | R | . | . | . | R | R | . |
| 117-5,80-82 | R | . | . | R | . | . | F | F | R | R | R | F | . | . | . | . | . | F | R | . | R | F | R | R | F | R | R | R | F | . | . | . | . | . | R | . | . | . | R | R | A | . | R | R | . | . | R | F | . |
| 118-1,44-46 | . | . | . | . | . | . | F | F | R | . | R | F | . | . | R | . | . | F | R | . | R | F | R | R | F | R | R | R | F | . | . | . | . | . | R | . | . | . | R | F | A | . | R | . | . | . | R | R | . |
| 118-5,147-147 | . | . | . | . | . | . | R | R | R | . | . | R | . | . | . | . | . | R | . | . | . | R | R | . | R | R | R | . | R | . | . | . | . | . | R | . | . | . | . | R | F | . | R | . | . | . | R | R | . |
| 119-4,42-44 | R | . | R | . | . | . | R | R | R | . | . | R | . | . | . | . | . | . | . | . | . | R | . | . | R | . | . | . | R | . | . | . | . | R | R | . | . | . | . | R | F | . | . | . | . | . | R | R | . |
| 120-1,63-64 | R | . | . | . | . | . | F | F | R | . | . | F | R | . | . | . | . | . | . | . | . | R | F | C | R | . | R | R | R | . | R | . | . | . | R | . | . | . | R | R | A | . | R | . | . | R | R | R | . |
| 120-2,100-102 | R | . | . | R | . | . | F | R | . | . | . | F | . | . | . | . | . | . | . | . | R | R | R | . | R | R | . | . | F | . | R | . | . | . | R | . | . | . | . | F | C | . | . | . | . | . | R | F | . |
| 120-3,58-59 | R | R | . | . | . | . | F | F | R | . | . | R | . | . | . | . | . | . | . | . | . | R | R | . | F | R | R | . | R | . | . | . | . | . | R | . | . | . | . | R | A | . | . | R | . | . | R | R | . |
| 120-4,103-105 | R | R | . | . | . | . | F | F | R | R | . | R | . | . | . | R | . | R | R | . | R | R | F | R | F | R | . | R | R | . | R | R | . | . | R | . | . | . | R | R | A | . | R | R | . | . | F | R | . |
| 120-6,134-136 | R | F | R | R | . | . | F | F | R | R | R | F | R | . | . | . | . | R | R | . | R | F | R | R | F | R | . | . | R | . | . | . | . | . | R | . | . | . | R | R | C | . | R | R | . | . | R | R | . |
| 121-1,24-25 | R | R | . | . | . | . | C | F | R | . | R | R | . | . | . | . | R | R | R | . | . | R | R | R | R | R | . | R | R | . | . | . | . | . | R | . | . | . | . | F | A | . | . | . | . | . | R | R | . |
| 121-3,58-59 | . | R | . | . | . | . | F | F | R | . | R | R | R | . | . | . | . | . | . | . | R | F | R | R | F | R | R | . | R | R | . | . | . | . | R | . | . | R | . | R | A | . | . | . | . | . | R | R | . |
| 121-4,30-31 | . | R | R | R | . | . | F | F | R | . | . | F | . | . | . | . | . | . | . | . | R | F | F | . | F | R | R | . | R | R | R | . | . | . | R | . | . | R | . | R | A | . | . | . | . | . | R | R | . |
| 121-6,138-142 | R | R | . | . | . | . | F | F | R | . | . | R | . | . | . | . | . | . | . | . | . | F | R | R | F | R | . | . | F | R | . | . | . | . | R | . | . | . | R | R | A | . | . | . | . | R | R | R | . |
| 122-1,67-69 | . | R | . | . | . | . | R | R | . | . | . | R | R | . | . | . | . | . | . | . | . | R | R | R | R | . | R | . | R | . | . | . | . | . | . | . | . | . | . | R | C | . | . | R | . | . | R | R | . |
| 122-2,131-133 | . | . | . | . | . | . | F | R | R | . | . | R | . | . | . | . | . | . | . | . | R | R | R | . | R | R | R | . | R | . | . | . | . | . | . | . | . | . | R | R | C | R | R | R | . | . | R | F | . |
| 122-3,41-42 | . | R | . | R | . | . | F | R | R | R | R | R | . | R | . | . | . | C | F | . | R | R | R | F | F | R | . | R | R | R | . | . | . | . | R | . | . | . | . | R | A | . | . | . | . | R | R | F | . |
| 122-4,100-102 | R | . | . | . | . | R | F | F | R | . | . | R | . | . | R | . | . | . | . | . | . | F | R | R | C | R | . | R | R | R | . | . | . | . | . | . | . | . | . | F | A | . | R | . | . | R | R | F | . |
| 122-6,33-34 | . | R | . | R | . | . | R | R | . | R | R | R | . | . | . | . | . | . | R | . | R | F | R | R | F | . | R | . | R | . | . | . | . | R | R | . | . | . | . | R | C | . | R | . | . | R | R | R | . |
| 122-7,23-24 | . | R | . | . | . | . | F | F | R | . | . | R | . | . | . | . | . | . | . | . | R | R | R | F | F | R | . | . | F | . | . | . | . | . | R | . | . | . | R | R | C | . | R | . | . | . | R | F | . |
| 123-1,49-50 | . | . | . | . | R | . | F | F | R | . | . | R | . | . | . | . | . | . | R | . | R | R | C | R | C | . | . | . | C | R | . | . | . | . | R | . | R | R | R | F | A | . | R | R | . | . | R | F | . |
| 123-2,35-36 | . | . | . | . | . | . | F | F | R | . | . | R | R | . | . | . | . | . | . | . | . | F | F | R | F | R | . | . | R | R | R | . | . | . | . | . | . | R | R | . | A | . | . | R | . | . | R | R | . |
| 123-3,48-49 | . | . | R | . | . | . | F | F | R | . | . | F | . | . | . | . | . | . | . | . | R | R | F | R | F | . | . | . | R | R | . | . | . | . | R | . | . | . | . | R | A | . | . | . | . | . | R | F | . |
| 123-4,96-97 | . | . | . | . | . | . | R | R | . | . | . | R | . | . | . | . | . | . | . | . | . | . | . | . | . | . | R | . | R | . | . | . | . | . | . | . | . | . | . | R | F | . | . | . | . | . | R | R | . |
| 123-5,39-40 | R | . | . | . | . | . | F | R | R | R | R | F | . | . | . | R | . | A | F | R | . | F | R | R | F | . | . | . | R | . | . | . | . | . | R | . | . | . | R | R | A | . | R | . | . | . | R | R | . |
| 124-1,17-18 | R | . | R | R | . | . | F | F | R | R | R | F | R | . | . | R | R | C | R | . | R | F | R | R | F | . | . | R | F | . | . | . | R | . | R | . | . | . | R | F | A | . | R | . | . | . | R | F | . |
| 124-4,45-47 | . | . | R | . | . | . | F | . | . | . | R | R | . | . | . | . | . | F | . | . | . | . | . | . | R | . | R | R | R | . | . | . | . | . | . | . | . | . | R | . | A | . | . | R | . | R | R | R | . |
| 125-6,64-65 | R | . | R | . | . | . | F | F | R | R | R | R | . | . | . | R | . | . | R | . | . | R | R | R | F | R | . | . | F | . | . | . | . | . | R | . | . | . | R | R | C | . | . | . | . | . | R | F | . |
| 125-5,113-115 | R | . | R | R | . | . | F | R | R | R | R | R | R | R | . | . | . | . | A | . | . | F | R | R | R | R | R | R | R | . | . | R | . | . | R | R | R | R | R | R | A | . | R | R | . | . | R | F | . |
| 126-1,120-122 | R | . | . | R | . | . | F | F | R | R | R | R | . | . | . | . | . | F | R | . | . | R | R | . | F | R | R | R | R | . | R | . | . | R | R | . | . | . | . | R | A | . | . | R | . | . | R | R | R |
| 126-2,43-44 | R | . | . | . | . | . | C | R | R | R | . | R | R | . | . | . | . | C | F | . | . | F | F | R | C | R | R | F | F | . | R | . | . | . | R | . | R | . | R | F | A | . | . | R | . | . | R | R | R |
| 126-3,110-113 | . | . | R | . | . | . | F | F | R | R | R | F | . | . | . | . | . | . | . | . | . | F | F | R | C | R | R | R | F | . | . | . | . | . | R | . | . | . | R | F | A | . | . | . | . | . | R | R | . |
| 126-4,57-58 | R | . | R | . | . | . | C | F | R | . | . | F | R | . | . | . | . | . | . | . | . | F | F | R | F | R | R | R | F | . | . | . | . | . | R | . | . | . | R | F | A | . | . | . | . | . | . | F | . |
| 126-5,113-115 | . | . | R | R | . | . | R | F | R | R | R | F | R | . | . | . | . | . | . | . | . | F | R | R | F | R | . | . | R | . | . | . | . | R | R | . | . | . | R | F | C | . | . | R | . | . | R | R | . |
| 126-6,37-38 | . | . | R | . | . | . | F | R | . | R | R | R | R | . | . | . | . | . | R | . | . | R | R | R | R | R | R | R | F | . | . | . | . | R | R | . | R | . | . | F | F | . | R | R | . | R | R | F | R |
| 127-1,20-21 | R | . | R | R | . | . | F | F | R | R | R | R | R | R | . | . | R | . | R | . | . | F | F | R | F | R | R | R | R | . | . | . | . | R | R | . | . | . | R | F | A | . | R | . | . | R | R | F | . |
| 127-2,53-55 | . | . | R | . | . | . | R | R | R | R | R | R | . | R | . | . | R | R | R | . | . | R | . | . | R | R | R | R | R | . | . | . | . | . | R | . | . | . | R | R | C | . | . | R | . | R | R | R | . |
| 127-3,102-104 | R | . | R | R | . | . | F | F | . | R | R | R | R | R | . | R | . | C | C | . | . | R | F | R | F | R | R | . | F | . | . | . | . | . | R | . | R | . | R | R | A | . | R | R | . | . | R | F | . |
| 127-4,45-46 | R | . | R | . | . | . | F | F | . | R | F | F | R | . | . | . | . | A | C | R | . | F | F | F | F | F | . | . | R | . | R | . | . | . | R | . | . | . | . | F | A | . | R | R | . | . | F | F | . |
| 127-5,25-26 | R | . | R | . | . | . | F | C | R | R | R | F | R | . | . | . | . | . | F | . | . | F | F | R | C | F | R | . | R | . | . | . | . | . | R | . | . | . | R | F | A | . | . | . | . | . | R | F | . |
| 127-6,64-65 | . | . | . | . | . | . | F | F | R | R | R | R | R | . | . | . | . | F | R | . | . | R | R | R | F | R | . | R | R | . | R | . | . | R | . | . | . | . | R | R | C | . | R | R | . | . | R | F | . |
| 128-1,40-41 | R | . | R | . | . | . | F | F | R | F | R | R | R | . | . | . | . | F | C | . | . | F | R | R | R | R | R | . | R | . | R | . | . | . | R | . | . | R | R | R | A | . | R | R | R | R | R | F | . |
| 128-2,35-36 | R | . | R | . | . | . | R | R | . | R | R | R | . | . | . | . | . | . | . | . | . | R | R | . | C | R | R | R | R | . | . | . | . | R | R | . | . | . | R | . | C | . | . | R | . | . | R | R | R |
| 128-3,32-33 | . | . | . | R | . | . | C | F | R | . | . | R | R | . | . | . | . | . | . | . | . | F | R | R | F | R | R | . | F | . | . | . | . | . | R | . | R | . | . | R | A | . | . | R | . | . | R | F | . |
| 129-1,125-127 | . | . | R | . | . | R | F | C | R | R | . | F | R | . | . | . | . | . | . | . | . | F | . | F | F | R | R | C | R | . | R | R | . | . | R | . | R | R | R | F | A | . | R | R | . | . | F | F | . |
| 129-2,44-45 | . | . | R | . | . | . | F | F | R | C | . | F | R | R | . | . | . | A | F | . | . | C | C | R | C | R | R | R | F | . | . | . | . | . | R | . | . | . | R | F | A | . | . | . | . | . | F | C | . |
| 129-3,126-128 | . | . | . | R | . | . | R | R | . | R | . | R | . | . | . | . | . | C | F | . | . | R | R | . | R | . | . | . | R | . | R | . | . | R | R | . | . | . | R | R | C | . | . | . | . | . | R | R | . |
| 129-4,61-62 | . | . | R | . | . | . | F | F | R | R | R | F | R | . | . | . | . | A | C | . | . | F | R | R | C | R | R | R | R | . | . | R | . | R | R | . | . | R | . | R | A | . | . | R | . | . | R | F | . |
| 129-5,119-121 | . | . | . | . | . | . | F | F | R | R | . | F | R | . | . | . | . | C | C | . | . | F | F | R | F | R | R | R | R | . | . | . | . | . | R | . | . | . | . | F | A | . | R | . | . | R | F | F | . |
| 129-6,42-43 | . | . | . | . | . | . | R | R | R | R | R | R | . | . | . | . | . | C | R | . | . | C | R | R | F | R | . | R | R | . | . | . | . | . | R | . | . | . | R | R | A | . | R | . | . | R | R | F | . |
| 129-7,9-10 | . | . | . | R | . | . | F | F | R | R | R | R | . | R | . | . | . | C | C | . | . | R | F | R | F | R | . | . | R | . | . | . | R | . | R | . | . | . | . | R | A | . | . | . | . | . | R | F | . |

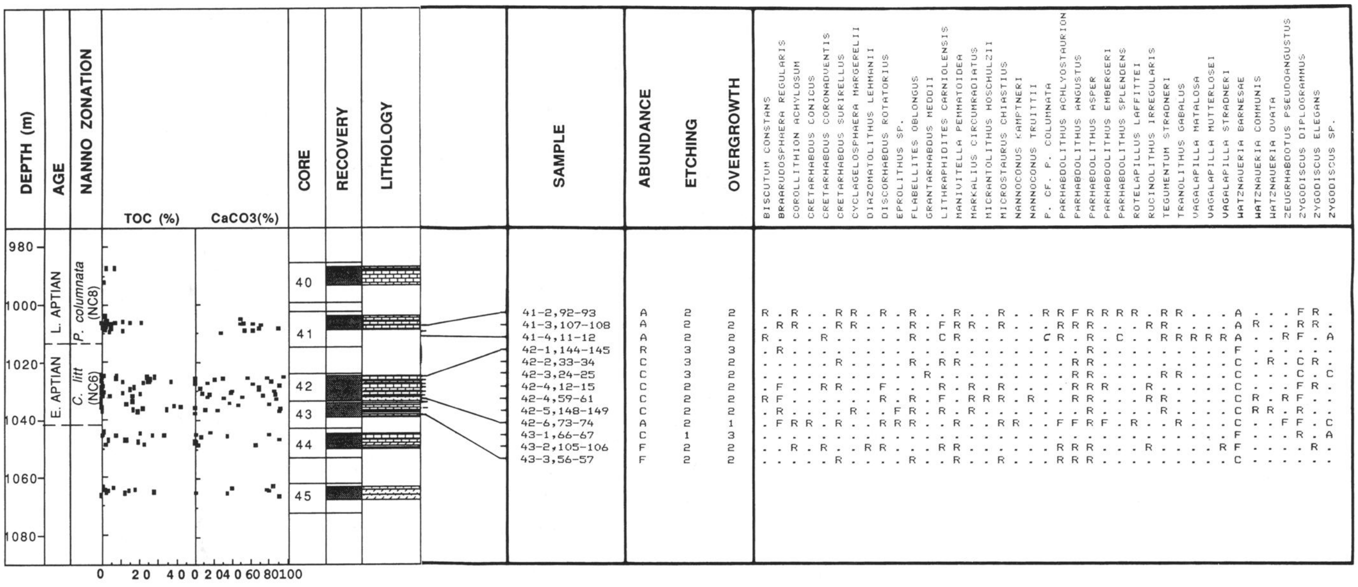


**FIGURE 6**—Range chart of calcareous nannofossils in DSDP Site 364. Nannofossil zonation is shown at left. Organic carbon data are taken from the literature (Table 1) and obtained as part of this study. Recovery shows gaps in section in white. See key for explanation of lithologic and biostratigraphic symbols.

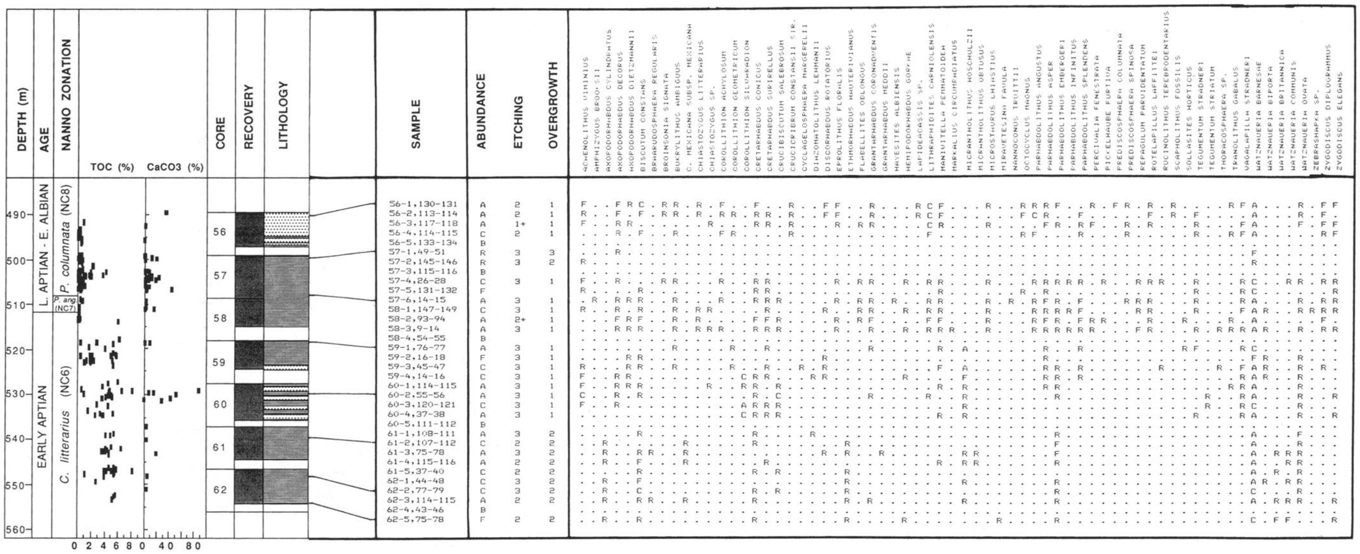


**FIGURE 7**—Range chart of calcareous nannofossils in DSDP Site 511. Nannofossil zonation is shown at left. Organic carbon data are taken from the literature (Table 1) and obtained as part of this study. Recovery shows gaps in section in white. See key for explanation of lithologic and biostratigraphic symbols.

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**FIGURE 5A**—Range chart of calcareous nannofossils in DSDP Hole 398D. Nannofossil zonation is shown at left. Organic carbon and carbonate data are taken from the literature (Table 1) and obtained as part of this study. Recovery shows gaps in section in white. See key for explanation of lithologic and biostratigraphic symbols.

**FIGURE 5B**—Range chart of calcareous nannofossils in DSDP Hole 398D. See Figure 5A for complete explanation.

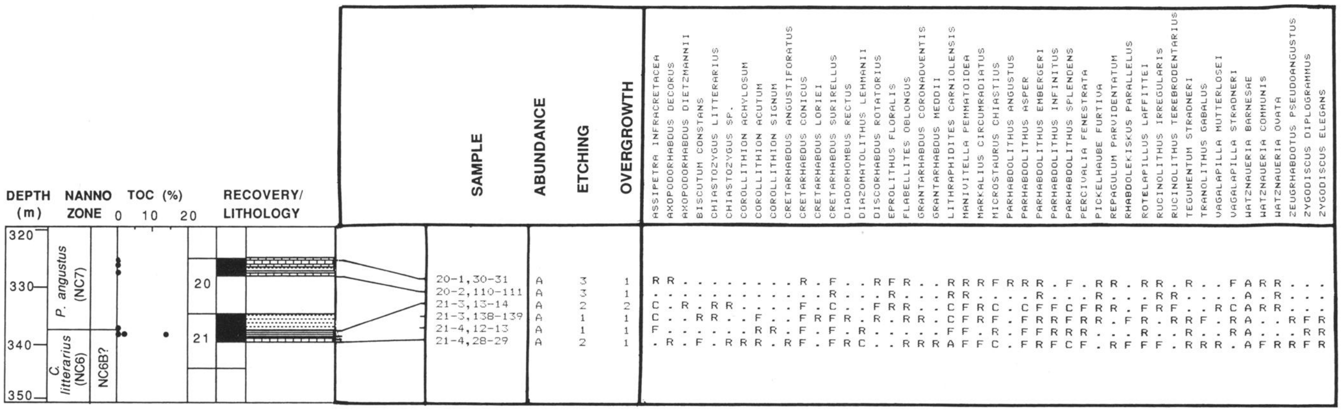

**FIGURE 8**—Range chart of calcareous nannofossils in DSDP Hole 417D. Nannofossil zonation is shown at left. Organic carbon data are taken from the literature (Table 1) and obtained as part of this study. Recovery shows gaps in section in white. See key for explanation of lithologic and biostratigraphic symbols.

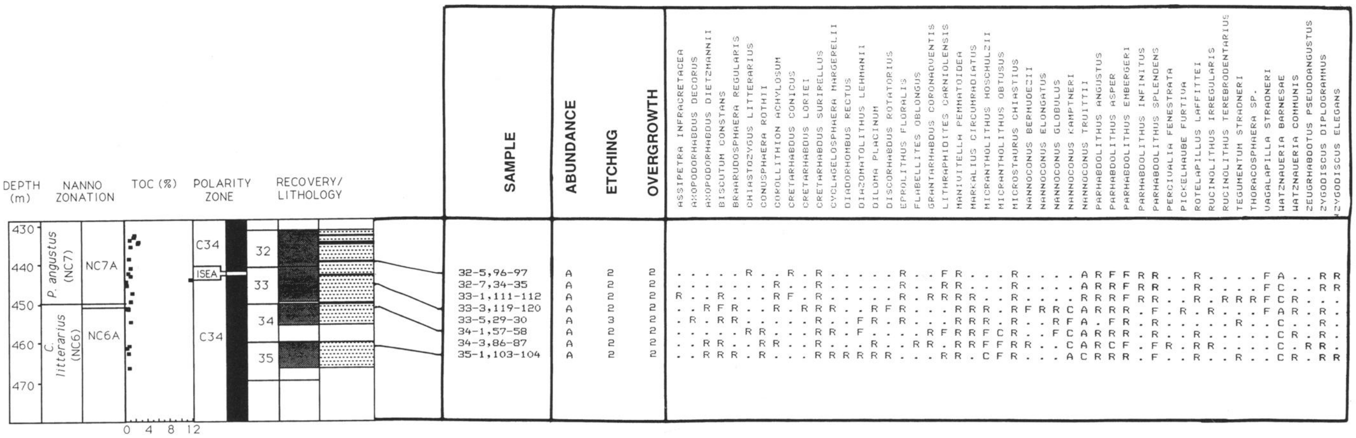

**FIGURE 9**—Range chart of calcareous nannofossils in DSDP Hole 402A. Nannofossil zonation is shown at left. Organic carbon data are taken from the literature (Table 1) and obtained as part of this study. Recovery shows gaps in section in white. See key for explanation of lithologic and biostratigraphic symbols.

*mannii, Micrantholithus hoschulzii* and *M. obtusus* upward but does not appear to have significantly altered the LO's of other species (e.g., *Cretarhabdus angustiforatus* and *Conusphaera rothii*) as the relative order of these events with first occurrences is similar to Hole 641C. The results obtained in our investigation of Hole 398D differ somewhat from those of Blechschmidt (1979) even though the Barremian/Aptian boundary assignment in Core 398D-123 is similar.

The order of the twelve biohorizons in Holes 398D and 641C are rather similar (Table 2). This is not surprising considering the close proximity of these sites. We use this order in the biostratigraphy developed (Fig. 3) even though it is likely that future studies from other expanded sections might modify these results. Most of these biohorizons cannot be determined precisely in the other sites investigated here, although the zonal markers can. The FO of *Eprolithus floralis* can be determined in all of the sections investigated with the exception of Vergons where it lies above the studied interval (Fig. 13; Table 2). The FO of *Rucinolithus irregularis* can be detected in all sections except DSDP Sites 417 and 463 where it lies below the studied interval (Figs. 8, 11), and DSDP Site 511 and ODP Site 763 where the low diversity assemblages in this interval do not contain this species (Figs. 7, 12). Our results lead us to concur with Wiegand (1984) and Erba (1988) that the FO of *Eprolithus floralis* is a better marker for the base of the *Parhabdolithus angustus* Zone (NC7; zonal abbreviation scheme of Roth (1978)) than the FO of the nominate taxon. *E. floralis* is more common and taxonomically distinct and our emended definition of *P. angustus* places its first occurrence in the latest Barremian. We define the base of the *Chiastozygus litterarius* (NC6) Zone by the FO of *Rucinolithus irregularis,* as this species is more common and less taxonomically problematic than the nominate taxon.

Only one other event can be confidently determined in the sections investigated, the LO of *Conusphaera rothii*/

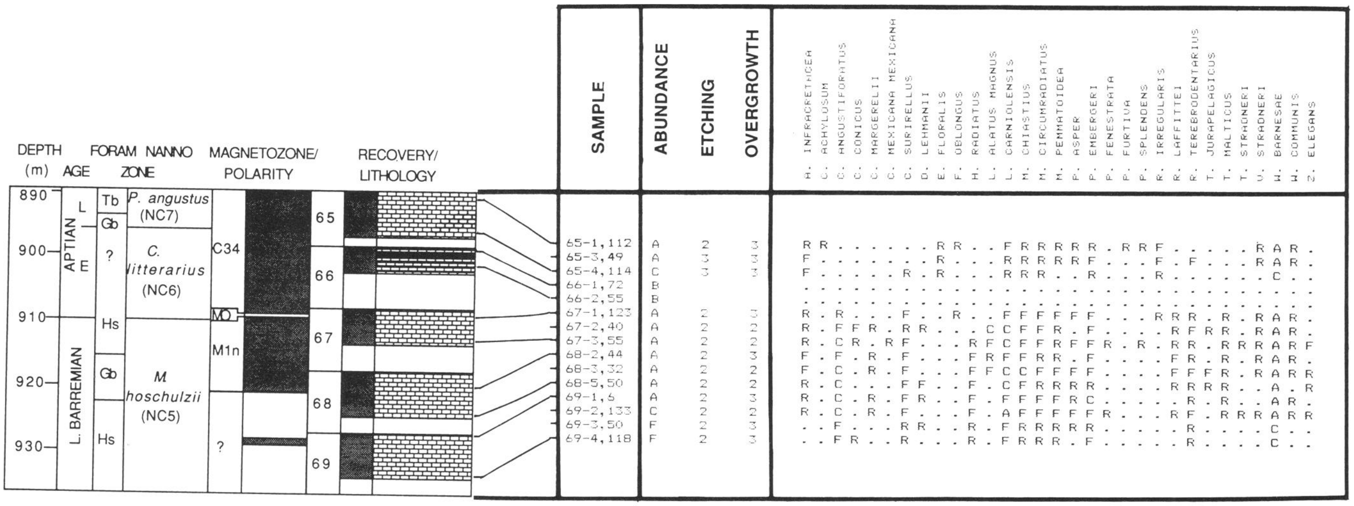

**FIGURE 10**—Range chart of calcareous nannofossils in DSDP Site 167. Nannofossil zonation is shown at left. Magnetostratigraphy after Taduno et al. (1989). Recovery shows gaps in section in white. See key for explanation of lithologic and biostratigraphic symbols.

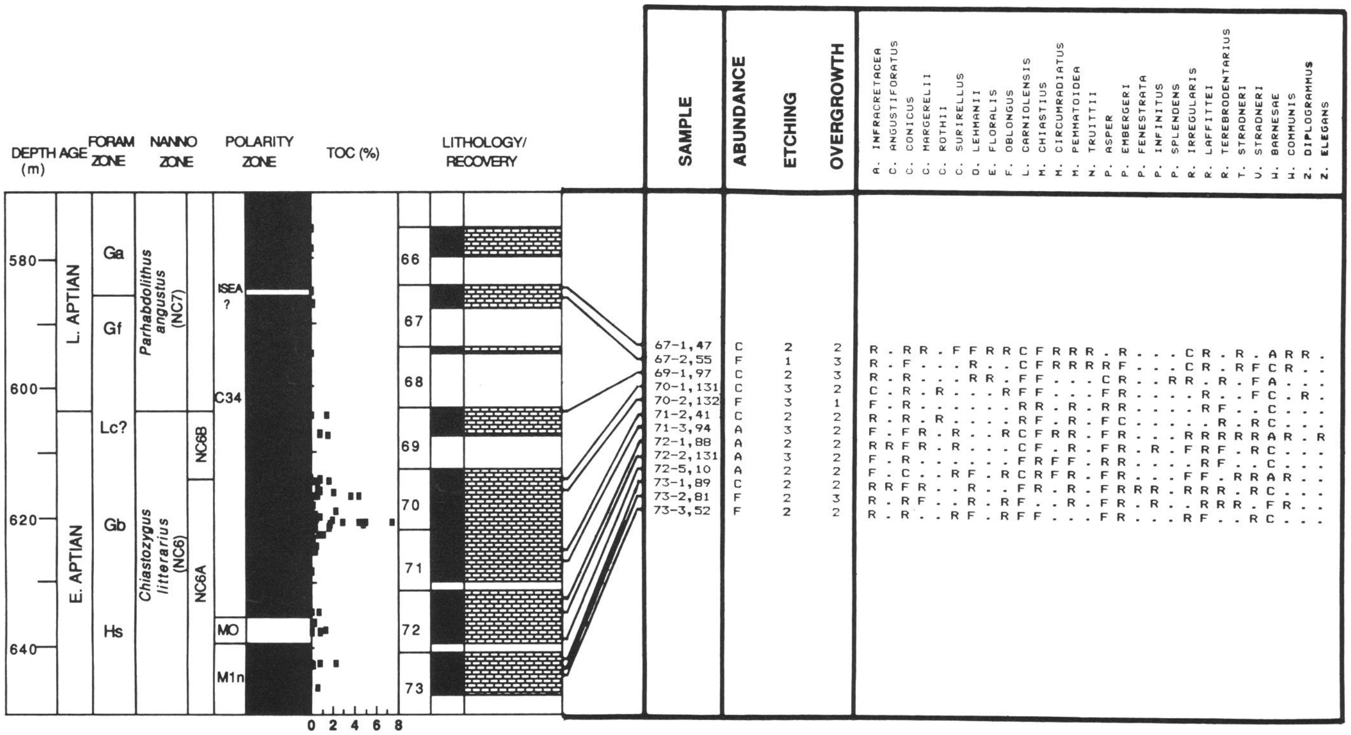

**FIGURE 11**—Range chart of calcareous nannofossils in DSDP Site 463. Nannofossil zonation is shown at left. Organic carbon data are taken from the literature (Table 1) and obtained as part of this study. Magnetostratigraphy after Tarduno et al. (1989). Recovery shows gaps in section in white. See key for explanation of lithologic and biostratigraphic symbols.

*C. mexicana* subsp. *mexicana*. These forms have been differentiated (Jakubowski, 1987), but may represent variable preservational states of the same taxon as their ranges appear to be identical. Since *C. rothii* is the more common of these two forms in this interval, we use the last occurrence of this taxon to divide the *C. litterarius* Zone into two subzones, the *C. rothii* Subzone (NC6A) below and the *Grantarhabdus coronadventis* Subzone (NC6B) above (Fig. 3; see Appendix II for formal definitions). This event can be readily detected in DSDP/ODP sites with good

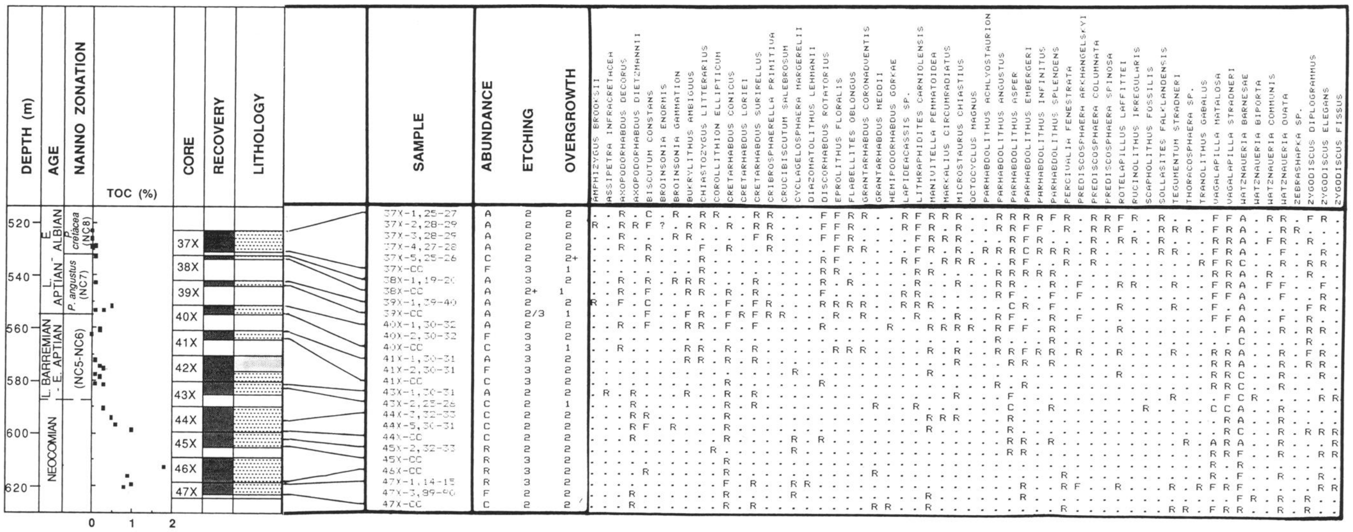

**FIGURE 12**—Range chart of calcareous nannofossils in ODP Hole 763B. Nannofossil zonation is shown at left. See Bralower and Siesser (1992) for more details on nannofossils biostratigraphy. Organic carbon data are taken from the literature (Table 1) and obtained as part of this study. Recovery shows gaps in section in white. See key for explanation of lithologic and biostratigraphic symbols.

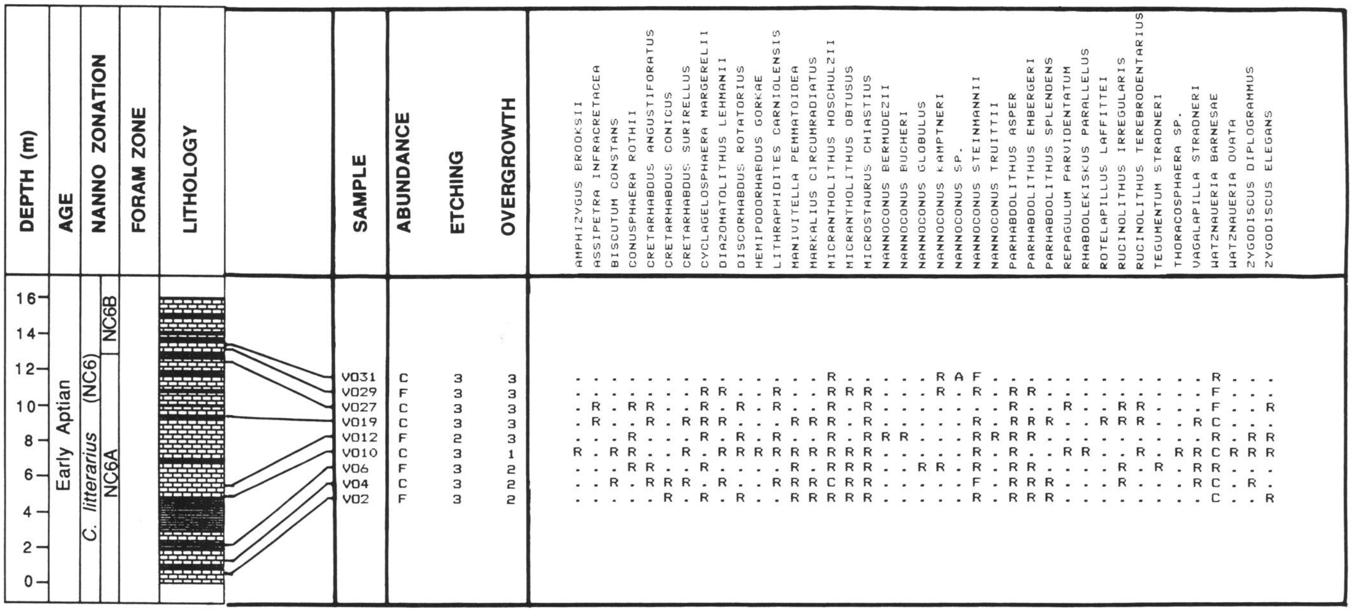

**FIGURE 13**—Range chart of calcareous nannofossils in the Vergons Section. Nannofossil zonation is shown at left. See key for explanation of lithologic and biostratigraphic symbols.

preservation, such as Sites 398, 511 (*C. mexicana* subsp. *mexicana*) and 641 (Figs. 4, 5, 7), but can only be determined with difficulty in the land sections (Figs. 14–16). The absence of this species in other sections (e.g., Site 417) indicates that the sampled interval lies above its last occurrence.

In summary, results of the nannofossil biostratigraphic investigation show that potential stratigraphic resolution in the early Aptian interval is high. To estimate the magnitude of this resolution, we assume an average sedimentation rate of 6.4 m/m.y. in ODP Hole 641C based on a duration of 0.56 m.y. for Chron M-0 which lies in Core 641C-10 (Ogg, 1988). The 7 nannofossil events in the *Chiastozygus litterarius* Zone are spread out over a 26 m interval giving an average of 0.58 m.y. between biohorizons.

## Planktonic Foraminifers

Standard late Barremian-early Aptian planktonic foraminifer biostratigraphy has developed over the years, with

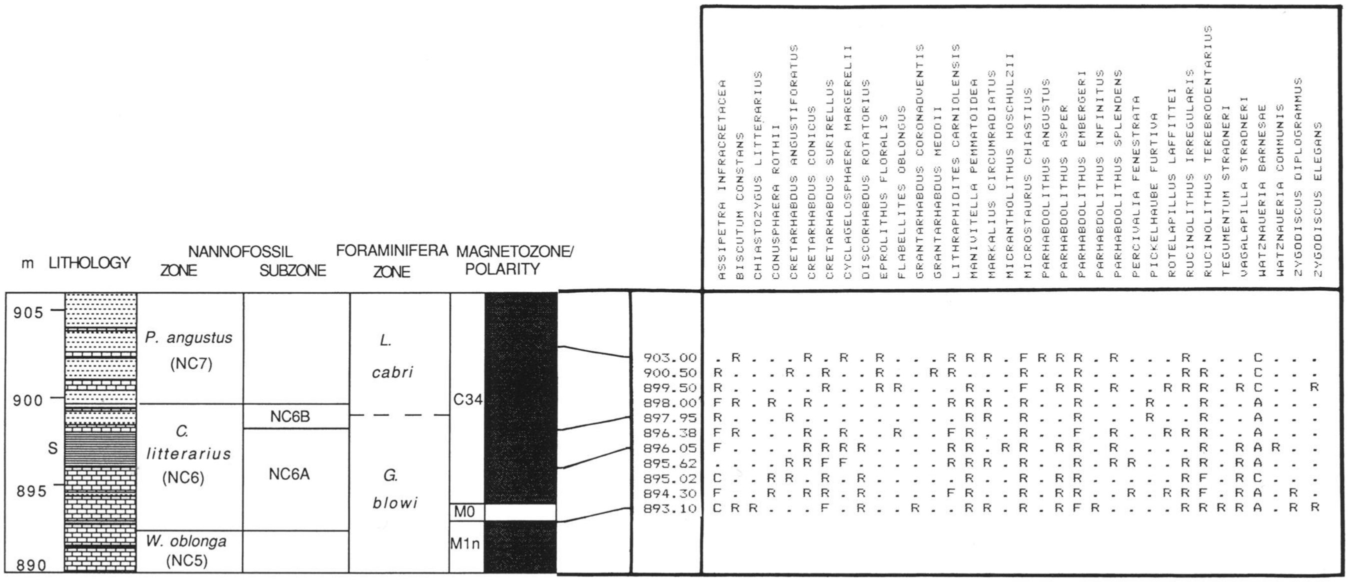

**FIGURE 14**—Range chart of calcareous nannofossils in the Gorgo a Cerbara Section. Nannofossil zonation is shown at left. Magnetostratigraphy from Lowrie and Alvarez (1984). See Bralower (1987) for more details on nannofossil biostratigraphy. Recovery shows gaps in section in white. See key for explanation of lithologic and biostratigraphic symbols. S indicates position of the "Livello Selli."

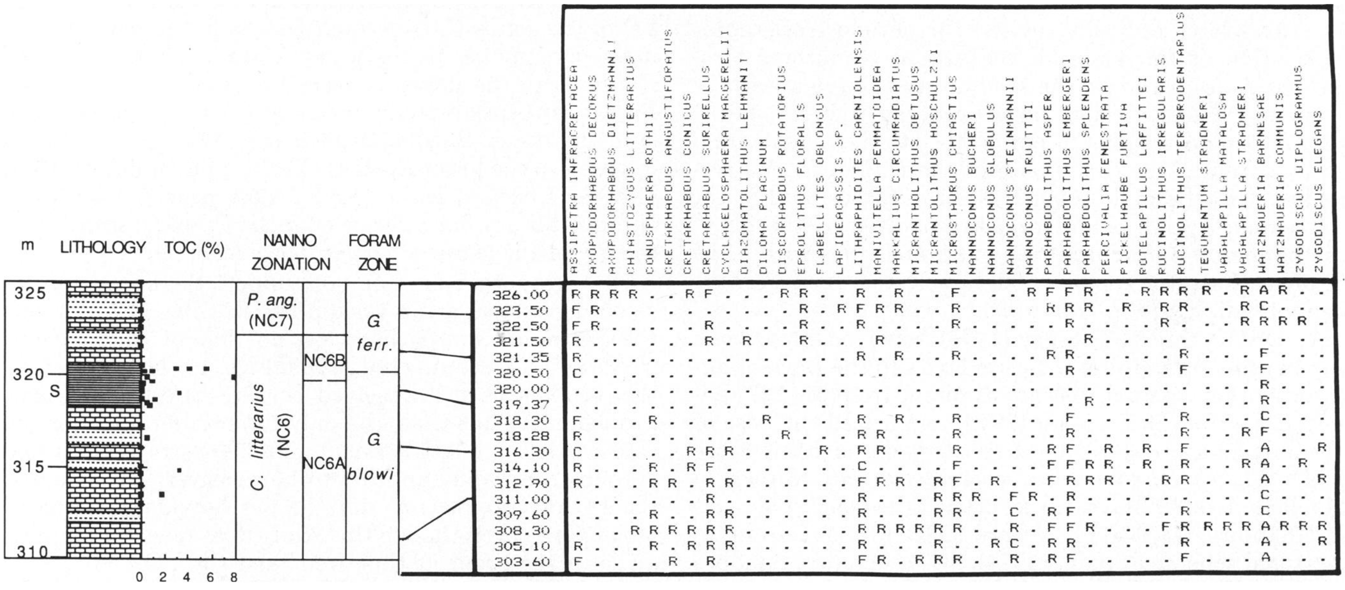

**FIGURE 15**—Range chart of calcareous nannofossils in the Piobbico Road Section. Nannofossil zonation is shown at left. See key for explanation of lithologic and biostratigraphic symbols. S indicates position of the "Livello Selli."

the zonations proposed by Longoria (1974) and Sigal (1977) having been most widely utilized. This latter scheme as modified by Sliter (1989b) consists of three interval zones, the *Hedbergella similis, Globigerinelloides duboisi* and *G. blowi* Zones, the bases of which are defined by the FO's of the nominate species. The top of the *G. blowi* Zone is defined by the FO of *Leupoldina cabri*, the nominate species of the overlying total range zone. According to numerous authors (e.g., Moullade, 1966; Sigal, 1977; Channell et al., 1979; Lowrie et al., 1980; Sliter, 1989b), the FO of *H. similis* approximates the Barremian/Aptian boundary and correlates with earliest magnetic Chron CM0.

Recently, however, Leckie and Bralower (1991) found numerous traditionally lower Aptian foraminiferal marker species in the Barremian (chronostratigraphy based on nannofossil biostratigraphy and magnetostratigraphy) of ODP Site 641 in the eastern North Atlantic, including the first occurrence of species of *Globigerinelloides* (early Bar-

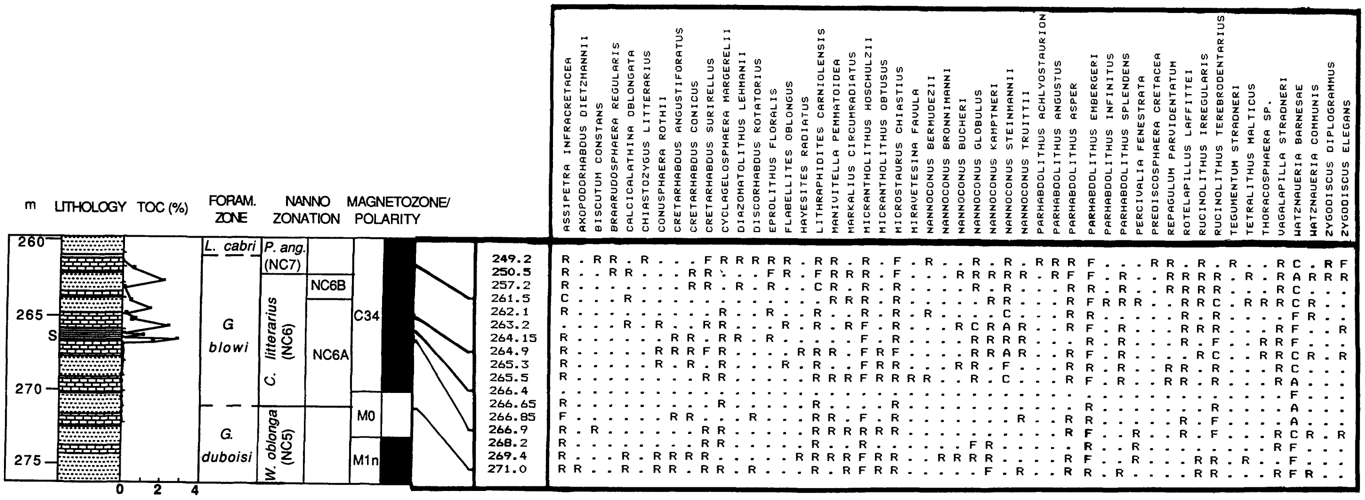

FIGURE 16—Range chart of calcareous nannofossils in the Cismon Section. Nannofossil zonation is shown at left. Magnetostratigraphy from Channell et al. (1979). See Bralower (1987) for more details on nannofossil biostratigraphy. See key for explanation of lithologic and biostratigraphic symbols. S indicates position of the "Livello Selli."

remian) and *H. similis* (near the early/late Barremian boundary). The latter age assignment had been previously proposed by Longoria (1984). In this regard, Coccioni et al. (1992) have radically revised the chronostratigraphic correlation of Barremian-lower Aptian planktonic foraminifer zones based on the study of the Gorgo a Cerbara sequence. These authors have proposed that: 1) the *H. similis* Zone correlates in part with late Barremian magnetic Chron CM2, 2) the base of the *G. blowi* Zone correlates with the middle part of Chron CMln, and 3) the Barremian/Aptian boundary, as recognized by the FO of the nannofossil, *Rucinolithus irregularis,* lies within the *G. blowi* Zone, the top of which lies close to the FO of the nannofossil, *Eprolithus floralis.*

At DSDP Site 398, Sigal (1979) reported planktonic and benthic foraminiferal datum levels in the Barremian-lower Aptian interval that are different from his 1977 zonation. In Hole 398D, Sigal (1979) recognized the base of the Barremian by the FO of *Hedbergella sigali* in Core 398D-133. "*Clavihedbergella*" *eocretacea* (=aff. *simplex* of Moullade (1966)) and a taxon listed as *Globigerinelloides* sp. 132b also have FO's in Core 398D-133. According to the zonal scheme of Sigal (1977), "*C.*" *eocretacea* defines a total range zone in the upper lower Barremian and species of the genus *Globigerinelloides* do not occur until the basal Aptian. One of us (R.M.L.) has observed a species of *Globigerinelloides* (*G. duboisi-gottisi* group) co-occurring with "*C.*" *eocretacea* below the FO of *Hedbergella similis* in nearby Hole 641C. We have concluded that FO and LO of "*C.*" *eocretacea* are reliable datums in the lower Barremian following the zonal schemes of Moullade (1966) and Sigal (1977) (Leckie and Bralower, 1991). The LO of "*C.*" *eocretacea* in Core 398D-129 is followed by the FO of *H. similis* in Core 398D-128 and by the FO of *Globigerinelloides blowi* s.s. at the base of Core 398D-127. This sequence is also observed in Hole 641C. The chronostratigraphic position of this sequence of first and last occurrences is further constrained by the recognition of polarity zone M-0 at Site 641 (Ogg, 1988). Based on these two sites from eastern North Atlantic, it is now clear that: 1) the FO of the genus *Globigerinelloides* is in the lower Barremian (as opposed to the lower Aptian), 2) the FO of *H. similis* is in the upper Barremian (as opposed to at the Barremian/Aptian boundary), and 3) the FO of *G. blowi* is in the upper Barremian near the FO of *H. similis* (as opposed to the lower Aptian) (Leckie and Bralower, 1991; also see Coccioni et al., 1992). This provides a critical chronostratigraphic reference for the FO of *H. similis* and the FO of the genus *Globigerinelloides.*

However, other data do not support the above conclusions. In particular, in Pacific DSDP Sites 167 and 463, the FO of *H. similis* lies close to that of *Rucinolithus irregularis* (Tarduno et al., 1989; Figs. 10, 11). Therefore, this problem is still unsolved perhaps due to taxonomic problems. At this time, the only foraminiferal biohorizon whose position relative to nannofossil biostratigraphy and chronostratigraphy appears to be relatively consistent is the FO of *Leupoldina cabri* (upper boundary of the *G. blowi* Zone) even though this study does reveal some variation in the order of this event and the FO of the nannofossil *Eprolithus floralis* (Figs. 10, 11, 14–16). We point out that this discrepancy is minor considering the condensed stratigraphy and poor preservation of this interval in the land and Pacific DSDP sections on which the correlations have been based. Two proposed correlations between upper Barremian–lower Aptian planktonic foraminiferal and calcareous nannofossil zones and events are illustrated in Figure 3.

We have made the general observation that $C_{org}$-rich horizons generally correlate with the *Globigerinelloides blowi* Zone, whether it be the short interval of Sigal (1977) and Sliter (1989a, b) or the relatively long interval of Coccioni et al. (1992). However, because of the discrepancy of these various studies, we do not use foraminifer biostratigraphy further in the discussion of the timing of dysoxia/anoxia in the early Aptian interval.

## OCEANIC DYSOXIA/ANOXIA IN THE LATE BARREMIAN-EARLY APTIAN

Combined lithostratigraphic and biostratigraphic evidence suggests that many of the sites investigated were characterized by a relatively brief interval of peak oxygen deficiency in the early Aptian within a longer latest Barremian-early Aptian interval of intermittent dysoxia/an oxia. Relatively high $C_{org}$ concentrations result from a variety of processes, including high rain rates (fluxes) to sediments, relative lack of dilution by terrigenous and/or biogenic material, and preservation in an oxygen-deficient water column (e.g., Demaison and Moore, 1980). We infer the occurrence of dysoxic (i.e., $<0.2$ ml/l $O_2$) or anoxic conditions at or above the sediment/water interface directly from the presence of fine-scale sedimentary laminations or lack of bioturbation and absence of benthic body fossils (e.g., Rhoads and Morse, 1971; Savrda et al., 1984). This does not constitute proof that the overlying water column was devoid or nearly devoid of oxygen, or, in particular that $C_{org}$ enrichment was entirely a function of lower rates of $C_{org}$ oxidation by oxic organisms in the water column and sediment. In fact, there is some question about the relative efficiency of aerobic versus anaerobic processes in remineralizing organic matter (e.g., Canfield, 1988) and the role of anoxia in enhanced $C_{org}$ preservation in general (e.g., Pedersen and Calvert, 1990; Calvert et al., 1991; Betts and Holland, 1992); however, the problem is not resolved. In this study, we interpret finely laminated black shales or $C_{org}$-rich limestones as having been deposited in an oxygen-deficient water column, and the widespread occurrence of such lithologies as resulting from the expansion and intensification of mid-water to deep water oxygen deficits. As discussed later, we do not assume that the depletion of dissolved oxygen during these widespread events was necessarily the main reason for the $C_{org}$ preservation. Instead, we believe that higher primary productivity and depleted water-column dissolved oxygen combined to produce higher sedimentary $C_{org}$ contents, dominated by marine amorphous organic material (kerogen). However, we would also argue that the higher pyrolysis hydrogen indices typical of the kerogens in many of the sections deposited in deeper water (e.g., de Graciansky et al., 1982) require enhanced preservation of lipid-rich marine amorphous organic material, because high $C_{org}$ concentration and hydrogen-rich material are not characteristic of deep-water sediments today, even under regions of unusually high surface-water production. In the following, we discuss the combined biostratigraphic, lithostratigraphic, carbonate and $C_{org}$ data from the sequences investigated.

The sections investigated have rather variable distributions of $C_{org}$-rich sediments. In some, such as the three Italian sections and Pacific DSDP Sites 167 and 305, carbonaceous horizons have a limited stratigraphic extent and contrast markedly with surrounding marly and cherty limestones. In other sequences, a more complicated succession of $C_{org}$-rich sediments are intercalated with multicolored claystone, chalk and limestone. Examples include the Vergons Section of France, Atlantic DSDP/ODP Sites 364, 398, 402, 417, 511 and 641, Pacific DSDP Site 463 and Indian Ocean ODP Site 763.

The organic-rich horizon in the three Italian sections has been named the "Livello Selli" (Coccioni et al., 1987, 1989). This is a 1–3 m thick level of black, laminated claystone alternating with sandy layers enriched in radiolarians. Coccioni et al. (1987) divided the Selli into a green and a black interval. We combine these two units in our investigation and discussion. The Selli is almost entirely devoid of carbonate; however a few samples within the Piobbico Road and Cismon Sections contain sparse, etched nannofossil assemblages. In all of the Italian sections, the Selli occurs within a sequence of cherty and marly limestone and lies in the lower Aptian *Chiastozygus litterarius* nannofossil Zone (*Conusphaera rothii* Subzone), immediately above magnetic Chronozone M0 (Figs. 14–16). Numerous very thin (1–2 cm) layers of "black" shale typified by $C_{org}$ values of up to 3% at Cismon and 8% at Piobbico occur in the upper Barremian-lower Aptian interval. These layers are clearly different from the Selli both petrographically and geochemically (e.g., Pratt and King, 1986; Tornaghi et al., 1989) but indicate a relatively broad interval of intermittent oxygen deficiency.

The lowermost Aptian interval of the Vergons Section in southern France contains a twenty meter interval of alternating laminated and homogeneous shale, the "Niveau Goguel" of Bréhéret (1988), which can be correlated around the Vocontian trough. This section cannot be dated precisely owing to especially poor nannofossil preservation but lies within the *C. litterarius* Zone (between the FO of *Rucinolithus irregularis* and the FO of *Eprolithus floralis*) (Fig. 13). The lowest observed specimens of *R. irregularis* are at 1.3 m; however, it is likely that this level is not the true FO of this species. The apparent LO of *Conusphaera rothii* at 12.5 m would place the lower part of the section in the *C. rothii* Subzone. A laminated $C_{org}$-rich shale horizon lies between 3 and 4.5 m (Fig. 13), and is the potential equivalent of the "Livello Selli." An extended episode of intermittent dysoxia/anoxia in the late Barremian-early Aptian is suggested by numerous thinner laminated shale horizons which occur throughout the lowermost part of this section.

Poor recovery prevents determination of the exact lithostratigraphic sequence of upper Barremian-lower Aptian sections of the Pacific Ocean. Lower Aptian sediments of DSDP Site 463 in the Mid-Pacific Mountains consist of tuffaceous, silicified and pure limestone. Peak $C_{org}$ contents occur in a thick interval of laminated, dark limestone in Core 463-70 which lies within the *Conusphaera rothii* nannofossil Subzone (Fig. 11). However, portions of Cores 463-67 to 463-73 are also laminated (Dean et al., 1981). This interval of intermittent oxygen deficiency coincides with the *Conusphaera rothii* and lower part of the *Grantarhabdus coronadventis* nannofossil Subzones and overlaps magnetic Chronozone M0 (in Core 463-72). At DSDP Site 167 on the Magellan Rise, a restricted interval of dark laminated limestone in Core 167–66 occurs within a sequence of multicolored light-colored limestone (Winterer et al., 1973). This interval lies within the *C. litterarius* nannofossil Zone and slightly above Chronozone M0 (Fig. 10). It is not possible to define nannofossil subzonal units in this site as *Conusphaera rothii* is extremely rare.

Upper Barremian-lower Aptian sections in the Atlantic Ocean contain alternations between multicolored claystone, chalk and minor intervals of limestone and sandstone. Because of this complex lithostratigraphy, interpretation of the stratigraphic significance of organic-rich units often requires examination of $C_{org}$ and carbonate contents (Fig. 2). At DSDP Site 417 in the western North Atlantic, the lower Aptian consists of cyclic claystone, sandstone, chert and chalk. Several thin carbonaceous horizons are located in Sections 417D-21-1 to 21-3 with a maximum in $C_{org}$ contents (up to 21%) occurring in the latter section. These sediments lie within the *Grantarhabdus coronadventis* Subzone based on the presence of *Rucinolithus irregularis,* but absence of *Conusphaera rothii* and *Eprolithus floralis* (Fig. 8). Our results suggest that these carbonaceous horizons are not equivalents of the "Livello Selli," but represent slightly later oxygen-deficient intervals.

The section of interest in ODP Site 641 drilled on Galicia Bank, from Cores 641C-6R to 641C-16R, is also dominated by interbedded, laminated and bioturbated multicolored claystones. Black claystones occur from Sections 641C-16R to -9R, however, their concentration is highest in Core 641C-11R, in which they are largely laminated. The equivalent section recovered at nearby DSDP Site 398 on Vigo Seamount consists of variable proportions of burrowed and laminated siltstone and sandstone, and calcareous and radiolarian-rich mudstone. Interbedded in the sections recovered at Sites 398 and 641 are microturbidites, debris flow conglomerate, slumps and graded beds indicating deposition in a distal turbidite fan setting (Sibuet, Ryan et al., 1979; Boillot, Winterer, Meyer et al., 1987).

Highly variable and mostly low $C_{org}$ contents (with no clear maxima) characterize the upper Barremian-lower Aptian of DSDP Hole 398D and ODP Hole 641C (Figs. 4, 5). Carbonate data are more revealing showing abrupt minima close to 0% which reflect an absence of calcareous microfossils. These correspond to Cores 398D-118 to -119 and Core 641C-9R. This latter core lies within the *Conusphaera rothii* (NC6A) nannofossil Subzone, and slightly above magnetic Chronozone M0 (in Core 641C-10R). The interval in Hole 398D lies in the *Grantarhabdus coronadventis* (NC6B) Subzone and the lower part of the overlying *Parhabdolithus angustus* (NC7) Zone. The significance of these carbonate-free zones, which is thought to be related to the occurrence of intense dysoxia/anoxia, will be discussed below.

Fine alterations between laminated, dolomitic limestone, marl and laminated and homogeneous black shale occur in the lower Aptian to upper Aptian-lower Albian interval of Site 364 (Cores 364-40 to -45) in the Angola Basin (Fig. 6). The lowermost cores, 364-44 and -45, cannot be correlated due to the absence of nannofossils. Proto-Decima et al. (1978) placed the FO's of *Eprolithus floralis* and *Prediscosphaera cretacea* in Sections 364-42-4 and 41-2, respectively. We have not seen true *E. floralis* at this site (see Appendix I) and have determined the FO of *P. columnata* to lie in Core 364-40. We have observed numerous specimens of a precursor form of *P. columnata* which may have been identified as this marker taxon by Proto-Decima et al. (1978) in Core 364-41 (see Appendix I for full description). From the presence of *Corollithion achylosum,* the FO of which lies between the LO of *C. rothii* and the FO of *E. floralis* in Sites 641 and 398, it can be inferred that $C_{org}$-rich sediments in Cores 364-43 to 364-41 lie in the *G. coronadventis* Subzone (NC6B). Sediments in Site 364 are characterized by extremely high $C_{org}$ contents (up to 42%) (Foresman, 1978; Herbin et al., 1987; this study). Although there are no apparent stratigraphic patterns in these data, contents are somewhat lower in the upper Aptian-lower Albian interval than below (Fig. 2).

The lower Aptian interval in DSDP Hole 402A (Cores 402A-34 and -35) in the Bay of Biscay consists of alternating marly chalk and calcareous mudstone. Low $C_{org}$ contents (generally less than 1%) are recorded in this section with one high value of 12% lying in the *Parhabdolithus angustus* (NC7) Zone at the base of the upper Aptian (Fig. 9). An interval of reversed magnetic polarity in Core 402A-33 has been correlated with the ISEA interval observed in various locations (Tarduno, 1990). There is a possibility that organic-rich horizons in the underlying *C. litterarius* Zone were not cored as a result of poor recovery or of termination of this hole above the interval of interest.

High latitude DSDP Site 511 and temperate ODP Site 763 are difficult to correlate precisely because important marker species are absent (Figs. 7, 12). The lower Aptian section at DSDP Site 511 on the Falkland Plateau in the South Atlantic consists of light-colored homogeneous or finely laminated, black claystone interbedded with minor chalk. High (1–7%) $C_{org}$ contents occur in Cores 511-59 to -62 with no maxima. Numerous horizons in this interval are barren of microfossils. A sharp decrease in $C_{org}$ occurs at the base of Core 511-58 (Fig. 7) coinciding with a change in the type of organic matter from a mixture of terrestrial and marine to dominantly marine (Deroo et al., 1983) and in the composition of microfossil assemblages. Both calcareous nannofossils and planktonic foraminifers are diverse in the upper part of Core 511-58. The $C_{org}$ record shows a pronounced maximum (4.3%) in upper Aptian Core 511-57 (Fig. 7). The upper Neocomian to lower Aptian section at ODP Site 763 on the Exmouth Plateau, northwest Australia consists of claystone and siltstone with minor sandstone (Haq, von Rad, O'Connell et al., 1990). This section, from Cores 763B-37X to -47X, contains calcareous horizons, is faintly laminated in places, but has $C_{org}$ contents mostly less than 0.5% (Allard et al., in prep.).

In Sites 511 and 763, the FO of *Eprolithus floralis* lies in chalk directly above the uppermost shale; however in both sites, it is unclear whether this is a true FO as underlying sediments contain assemblages of low diversity. The only marker present in these sediments at DSDP Site 511 is *Conusphaera mexicana* subsp. *mexicana.* The last occurrence of this species in Section 511-61-2 would place underlying Sections (511-61-3 to -62-5) in the *C. rothii* Subzone and the overlying interval (Cores 511-59 and 511-60 and Sections 511-61-1 and 61-2) in the *G. coronadventis* Subzone. A few specimens of *Grantarhabdus coronadventis* in Section 511-62-3 are consistent with this age interpretation (Fig. 7) but the absence of the critical marker, *Rucinolithus irregularis,* reduces the certainty of these age constraints. Planktonic foraminifers and macrofossils indicate these cores are Barremian-Aptian (Krasheninnikov and Basov, 1983; Jeletzky, 1983). There are numerous reworked specimens of Jurassic nannofossil taxa in this interval, including *Axopodorhabdus cylindratus* and *Ethmorhabdus gallicus* (Wise, 1983; Fig. 7). We cannot rule out the possibility that specimens of *C. mexicana* subsp. *mexicana* observed in these same samples are also reworked. A magnetic polarity stratigraphy has been generated for this section (Salloway, 1983), with a mixed-polarity interval (presumed to be the M-sequence) extending downwards from Section 511-58-4. This reversed interval is considered unreliable as demagnetization is incomplete and inclinations are erratic.

ODP Site 763 presents a more difficult stratigraphic correlation problem. Low diversity nannofossil assemblages from Cores 763B-42X to 763B-47X contain no age-diagnostic species (Bralower and Siesser, 1992; Fig. 12). The interval from Section 763B-42X-5 to -45X-4 is middle Barremian to lower Aptian based on palynomorphs (Brenner, 1992). We speculate that dark claystones with low $C_{org}$ contents at Site 763 roughly correlate with lower Aptian carbonaceous deposits elsewhere.

Even though two of the sections investigated here, Sites 511 and 763 cannot be correlated precisely, biostratigraphic evidence from other sequences indicates that part of the early Aptian was characterized by a relatively brief dysoxic/anoxic episode on a nearly ocean-wide scale. Evidence for oxygen deficiency includes occurrence of a pronounced carbonaceous shale or limestone, such as the "Livello Selli" or "Niveau Goguel," a peak in $C_{org}$ contents, and/or a microfossil-free interval. We are aware of other $C_{org}$-rich horizons not studied here which appear to correlate with this early Aptian episode, including DSDP Site 361 in the Cape Basin, South Atlantic (Proto-Decima et al., 1978) and the Fischschiefer Level of northwestern Germany (e.g., Mutterlose and Harding, 1987). We follow the terminology of Schlanger and Jenkyns (1976) and Arthur et al. (1990) and use the term "oceanic anoxic sub event" (OASE) for the early Aptian interval of the Aptian-Albian OAE. Table 3 provides a summary of the timing of peak dysoxia/anoxia as well as intervals characterized by less intense oxygen deficiency. In many sites the peak of the proposed OASE lies within the *Conusphaera rothii* (NC6A) Subzone of the *Chiastozygus litterarius* nannofossil Zone, shortly after Chron CM0. In all sites with planktonic foraminiferal biostratigraphy, this peak lies within the *Globigerinelloides blowi* Zone regardless of its chronostratigraphic correlation. The record at several sites indicates that this peak lay within a somewhat lengthier, patchier dysoxic/anoxic interval which extended into the underlying late Barremian *Watznaueria oblonga* nannofossil Zone and the overlying *Grantarhabdus coronadventis* Subzone. There are a couple of anomalies to this, for example, in Sites 398 and 402 where the peak lies at a slightly higher level than in other sites.

Assuming a constant sedimentation rate for this interval at ODP Site 641, we can provide a rough estimate of 0.6 m.y. for the duration of peak dysoxic/anoxia as recognized by the calcareous microfossil-free interval in Core 641C-9R (see below for explanation). A similar method gives a duration of 0.9 m.y. in the Gorgo a Cerbara section. Using periodicities of Milankovitch cycles within the "Livello Selli," Herbert (1992) independently estimated the duration of this event to be 1–1.3 m.y. While peak dysoxia/anoxia was less than 1.5 m.y. in duration, the complete record of organic-rich sedimentation in the late Aptian spanned a longer interval of time, on the order of 2.5–3 m.y.

One final stratigraphic conclusion which is readily apparent is the condensed nature of the lower Aptian interval in many of the sections studied. At Sites 398 and 463, the *Grantarhabdus coronadventis* Subzone corresponds to 17 m and 9 m of section, respectively. This same interval is much thinner in all of the other sections in which it can be identified including Site 641 (2 m), Cismon (1 m), Piobbico Road (4 m) and Gorgo a Cerbara (1.5 m). This condensed interval, which may have resulted from a sea level transgression, hampers the accuracy with which events in the early Aptian can be deciphered.

## PALEOECOLOGY OF THE LATE BARREMIAN-EARLY APTIAN

Several problems render the ecological interpretation of nannofossil assemblages in ancient sections far more speculative than those of modern surface waters and sediments (e.g., McIntyre and Bé, 1967; McIntyre et al., 1970; Bukry, 1974). Besides diagenetic alteration (e.g., Hill, 1975), it is often difficult to isolate individual ecological factors which may have controlled the distribution of species. However, several studies have employed nannofossil assemblages as a tool in Mesozoic paleoceanography (e.g., Roth and Bowdler, 1981; Roth and Krumbach, 1986; Watkins, 1986), and there is a reasonable knowledge of the paleobiogeographic and paleoecological affinities of several taxa. Previous assemblage studies of the Barremian/Aptian boundary interval have been based entirely on the study of a single sequence (e.g., Coccioni et al., 1992). Although we have not carried out a quantitative assemblage analysis, observations of a number of sequences allow us to reach some general conclusions regarding the paleoecology of this time interval.

Upper Barremian-lower Aptian sediments in DSDP Site 511 and ODP Site 763, both located in restricted ocean basins at mid- to high-latitudes at the time of deposition, contain well-preserved, low diversity nannofossil assemblages dominated by various combinations of *Watznaueria barnesae, Repagulum parvidentatum, Vagalapilla matalosa, Crucibiscutum salebrosum, Corollithion silvaradion* and

*Micrantholithus hoschulzii* (Parker et al., 1983; Wise, 1983; Bralower and Siesser, 1992; this study). The former two species have been cited as having tolerances to extreme, although unspecified, environmental conditions based on their abundance in Valanginian and Aptian black shales from ODP Sites 692 and 693 (Weddell Sea), northwestern Germany and Site 511 (Mutterlose, 1989; Mutterlose and Wise, 1990). Factor analysis of middle Cretaceous North Atlantic, Indian Ocean and English Gault Clay nannoplankton assemblages has led to differentiation of *W. barnesae* as an indicator of low fertility and *R. parvidentatum* as an index of cold water (e.g., Roth and Krumbach, 1986; Erba et al., 1992). The abundance of the former taxon in $C_{org}$-rich sediments from these sites suggests that during at least part of the oxygen-deficient intervals, mid- to high-latitude surface waters were nutrient-depleted. However, it appears that peak dysoxia/anoxia, at least in the one section investigated, was characterized by quite different conditions. Nannofossil assemblages on both sides of the "Livello Selli" in the Gorgo a Cerbara section are relatively enriched in *Zygodiscus erectus* (Coccioni et al., 1992), a taxon which is indicative of higher fertility conditions (Roth and Krumbach, 1986).

Interesting patterns emerge when the distribution of nannofossils and planktonic foraminifers is observed in upper Barremian and lower Aptian sediments. In Sites 511 and 763, many samples are devoid of nannofossils and planktonic foraminifers. Other samples are barren of foraminifers, but contain low diversity assemblages of nannofossils. In several lower Aptian sections, sediments with the highest $C_{org}$ contents are barren of nannofossils and planktonic foraminifers. There include the "Livello Selli" (Coccioni et al., 1992) the "Niveau Goguel" and $C_{org}$-rich sediments from Site 417. Other sites, including 167, 398 and 641, contain intervals barren of calcareous microfossils which do not correspond to peaks in $C_{org}$ in these particular cores, but which do correlate stratigraphically with these peaks in other locations. Barren intervals in these sites often contain radiolarians, sparse arenaceous benthic foraminifers, belemnites, juvenile pelecypods and fish debris (Sigal, 1979; Jeletzky, 1983; Thurow, 1988; Premoli Silva et al., 1989).

The origin of these barren intervals and their significance in terms of the OASE as discussed in detail by Bralower et al. (1993) is summarized in the following. It is possible that there was a rise in the CCD coincident with the OASE and that the paleodepth of these sites were such that they lay below the CCD for a short period of time. While the CCD rose rather drastically in the early Aptian (Thierstein, 1979; Arthur and Dean, 1986), it is unlikely to have fluctuated drastically on time scales equivalent to some of the finer $C_{org}$-rich layers. Another possible explanation for the absence of carbonate in this interval is that highly corrosive waters associated with the combustion of large amounts of organic material, on the sea floor or during early diagenesis, led to the dissolution of nannofossil and planktonic foraminiferal tests. The feasibility of this latter mechanism is lessened, but not entirely ruled out, by the observation that at sites such as 398, 511 and 641, the barren intervals do not correspond to the highest enrichments in $C_{org}$.

Alternatively, it is possible that nannoplankton and foraminifers were both environmentally excluded during a brief interval of high productivity and associated oxygen deficiency. Because of their entirely different affinities and ecologies, it is likely that planktonic foraminifers and nannoplankton were absent for separate reasons. The production of modern coccolithophores, such as *Emiliania huxleyi,* tends to decrease in highly turbulent/highly fertile and in stratified water masses (Margalef, 1978) where they become less competitive than diatoms and dinoflagellates, respectively. A combination of these factors may have led to the absence of nannofossils in the intervals of interest, however, it is most likely that the peak of the dysoxic/anoxic interval corresponded to highly eutrophic conditions. Modern planktonic foraminifers are successful in moderately eutrophic regimes (Bé, 1977; Caron and Homewood, 1983; Hemleben et al., 1989), but are intolerant to oxygen deficiency. A feasible scenario is that an intensified oxygen minimum zone associated with high fertility caused the absence of planktonic foraminifers in several areas at times during the late Barremian-early Aptian. Even though nannoplankton and planktonic foraminifers may have suffered during a brief interval of adversity in particular locations, it is clear from the high species richness in overlying samples that the flora and fauna quickly reestablished themselves.

Assemblage data indicate highly variable productivity throughout the late Barremian-early Aptian with oligotrophic conditions in some $C_{org}$-rich intervals and eutrophic conditions in others. Geochemical evidence (Herbert et al., 1986; Pratt and King, 1986) suggests similar variability in limestone/marl-shale cycles with minor $C_{org}$-rich horizons in the Scisti a fucoidi representing oligotrophic intervals. No one model seems to account for oxygen-deficiency in this interval. There have been lengthy discussions in the literature as to whether middle Cretaceous $C_{org}$-rich sediments were produced as a result of high primary productivity (e.g., Schlanger et al., 1987; Leckie, 1989; Premoli Silva et al., 1989; Pedersen and Calvert, 1990) or effective preservation of that organic material produced (e.g., Bralower and Thierstein, 1984; Dean et al., 1986). Much of the debate is centered on the suitability of modern environments, such as the anoxic Black Sea, as analogs to the ancient settings that produced black shales (e.g., Pedersen and Calvert, 1990). If productivity varied significantly through time, as is likely, different interpretations of this problem may have resulted from the particular age and duration of the interval in question. The technique of Bralower and Thierstein (1984) estimated average paleoproductivity for zonal durations of 6–9 m.y. However, Schlanger et al. (1987) and this investigation have considered events less than 1 m.y. in duration.

The dysoxic/anoxic episode was not responsible for extinctions, with one possible exception. The Barremian/Aptian boundary interval has been cited as a time of crisis for the nannoconids (Coccioni et al., 1992). It has been suggested that this group were resting cysts produced by

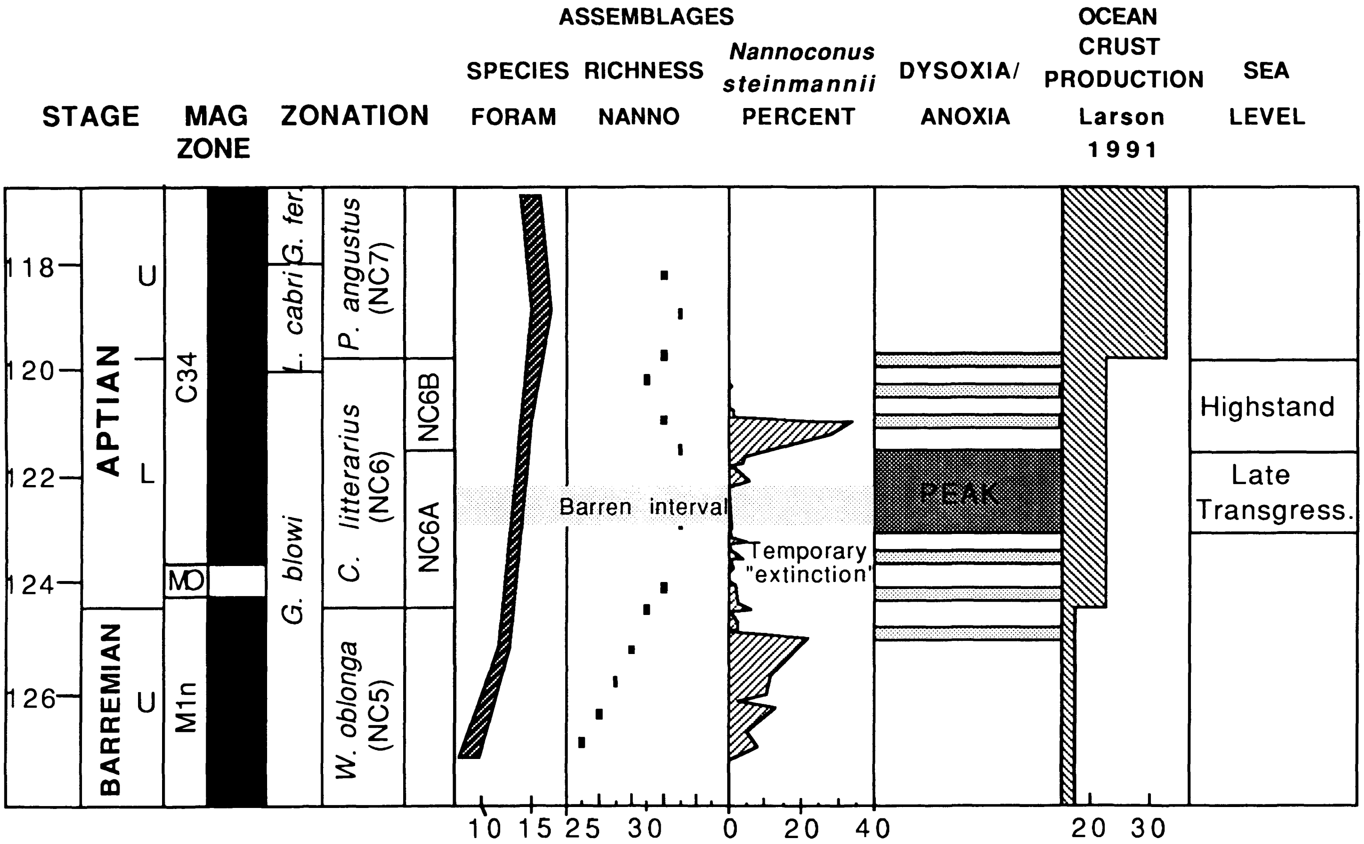

FIGURE 17—Stratigraphic summary of the late Barremian-early Aptian interval. The diagram shows: a synthesis of chronostratigraphy; nannofossil and foraminiferal species richness data (the former simplified from Site 641 showing FO's and LO's of marker taxa; the latter from Longoria (1974), Sigal (1979), Leckie (1989), Sliter (1989b) and Leckie (unpubl. stratigraphy of Hole 641C)); percent *Nannoconus steinmannii* taken from Bralower and Botelho (in prep.); schematized record of dysoxia/anoxia (results from this study); oceanic crustal production rates (in $10^6$ $km^3/m.y.$) (from Larson, 1991) and the sea level record (inferred from stratigraphy, see text for full discussion).

calcareous dinoflagellates much like modern *Thoracosphaera* (Busson and Noël, 1991). These authors also suggested that nannoconids thrived in oligotrophic conditions. Coccioni et al. (1992) suggested that the dramatic disappearance of the dominant taxon, *Nannoconus steinmannii* may have been related to widespread eutrophic conditions at the beginning of the oxygen-deficient episode. The current investigation suggests a slightly more complex situation. At several sites there is a short-lived temporary disappearance of this species beginning close to the Barremian/Aptian boundary followed by a brief reappearance before its final extinction. Directly overlying the barren interval (i.e., after peak oxygen deficiency) in Hole 641C (Sections 641C-8R-4 and -8R-5), assemblages are extremely enriched in *N. steinmannii* (Fig. 4). Similar enrichments also occur in sediments directly overlying the "Livello Selli" in the Cismon section (Fig. 16). These occurrences suggest the *N. steinmannii* reappeared in some places for a short time in the lingering stages of the dysoxic/anoxic episode (Fig. 17) so that its last occurrence is abruptly time-transgressive. The temporary disappearance of this taxon correlates with 11 m of section in Hole 641C (Fig. 4; only two specimens were observed in the interval from Sample 641C-11R-3, 36–37 cm, to -10R-2, 27–29 cm) and to 9 m of strata at Cismon (Bralower, 1987). A few samples in this interval in some sections contain rare occurrences of other species of nannoconids such as *N. kamptneri* and *N. globulus* (e.g., Figs. 4, 16). It is possible that the nannoconid crisis was a direct result of factors (e.g., eutrophication) responsible for the dysoxic/anoxic episode (e.g., Coccioni et al., 1992). However, it is likely that a more complex sequence of events were responsible as this group was already in trouble long before the peak of the dysoxic/anoxic interval and as the distribution patterns and timing of the extinction of the dominant taxon, *Nannoconus steinmannii* is distinctly variable.

The early Aptian is an interval of diversification of calcareous nannoplankton (Roth, 1987, 1989) and planktonic foraminifers (Leckie, 1989; Fig. 17). Previous studies of this phenomenon have been based on literature compilations of temporal changes in numbers of species, an approach which is inherently tied to changing preservation and differing taxonomic concepts of the various sources.

Our detailed nannofossil biostratigraphic study of the Barremian/Aptian boundary interval substantiates the diversification trend established by Roth (1987, 1989). However, our investigation shows that diversification began in the upper part of the *Watznaueria oblonga* (NC5) Zone (late Barremian) before peak dysoxia/anoxia. Both Roth (1987, 1989) and Leckie (1989) associated the diversification in this interval temporally and causally with OAE. Roth's (1989) scenario is that declining surface water fertility, associated with reduced vertical mixing and dysoxia/anoxia, resulted in higher rates of speciation as competition between species for nutrients increased. As discussed previously, fertility was probably highly variable in this interval. In addition, the timing of diversification, which began some 2–3 m.y. before peak dysoxia/anoxia indicates that another factor, possibly elevated sea level, may be a more likely causal factor. Planktonic foraminifers experienced their first major adaptive radiation during the Barremian-early Aptian interval. It has been proposed that rising sea level, expansion of marginal seas and the onset of dysoxic/anoxic-prone benthic conditions resulted in the exploitation of near surface waters and diversification of planktonic foraminifers (Caron, 1983; Leckie, 1989).

Our biostratigraphic evidence suggests that there was a brief interval in the early Aptian when calcareous plankton were eliminated in significant parts of the ocean. However, the plankton were able to survive in the long run, unlike the Cenomanian/Turonian boundary when there were major extinctions of planktonic foraminifers, ammonites and inoceramids (but not of nannoplankton) apparently as a direct result of anoxia (Raup and Sepkoski, 1982; Arthur et al., 1987; Bralower, 1988). Dysoxia/anoxia and related paleoecologic factors at this latter time led to the extinction of groups of newly-evolved deep-dwelling, keeled planktonic foraminiferal taxa with narrow ecologic tolerances and to the establishment of a low diversity fauna for an interval close to 1 m.y. (e.g., Hart and Bigg, 1981; Leckie, 1985, 1989). It is doubtful whether a deep-dwelling fauna had been established by the early Aptian, and this might explain the lack of extinctions of planktonic foraminiferal assemblages at this time.

## DISCUSSION

The origin of $C_{org}$-rich horizons in the ancient record remains controversial (e.g., Pedersen and Calvert, 1990), and those of the early Aptian OASE are no exception. Black shales, or relatively $C_{org}$-rich strata are typically assumed to represent oxygen-deficient conditions, as discussed earlier in this paper. In this regard, we do not argue that oceanic deep-water masses above the sites of preservation were necessarily entirely devoid of dissolved oxygen, only that many of the studied sites represent deposition under dysaerobic conditions ($<25$ $\mu$moles $O_2$/kg) because preservation of fine lamination suggests the exclusion of bioturbating metazoan organisms. We consider it likely that primary productivity also played a role in some regions through increased $C_{org}$ particle flux to the sediment/water interface. However, this is very difficult to demonstrate because of our inability to calculate component accumulation rates with any confidence, primarily because of the lack of a precise age-calibrated biostratigraphic framework.

Upper Barremian-lower Aptian black shales appear at sites in a variety of oceanographic settings. These include oceanic plateaus in the large Pacific Ocean Basin (DSDP Sites 167, 305 and 463), marginal oceanic platforms in the Tethys ("Livello Selli" of Cismon, Gorgo a Cerbara and Piobbico Road Sections, Italy), open ocean pelagic (DSDP Site 417) and hemipelagic deep continental margin regions in the Atlantic basins (paleodepths 500–3000 m; DSDP Sites 364, 398, 402 and 511, ODP Site 641) and Indian Ocean (ODP Site 763), and epicontinental seaways of Europe ("Niveau Goguel" in the Vocontian Trough; black shale facies in north Germany).

While it appears that the early Aptian OASE had an ocean-wide distribution, the record of this event varies drastically in different settings, primarily in terms of the stratigraphic range over which $C_{org}$-rich strata occur. At many localities, the early Aptian OASE appears to have been a relatively brief event, occurring across a sedimentary thickness of 5 meters or less. The sharpness of the event in these sites may be a function of the very condensed record of this interval, perhaps because of deposition during rapid sea level rise (see below). The most "complete" (in terms of thickness) record of the OASE is in hemipelagic (high sedimentation rate) continental margin sites such as DSDP Sites 398 and 511 and ODP Sites 641 and 763. Two of these DSDP Site 511 and ODP Site 763, were located in temperate and high-latitude basins which may have been somewhat tectonically restricted and, therefore, more sensitive to processes, such as stable stratification, poor deep-water exchange and/or high primary productivity, that caused water-column oxygen depletion even before the OASE began. It is much more difficult to detect the early Aptian OASE as a distinct lithologic or biostratigraphic horizon in these sites. Nonetheless, Sites 511 and 763, as well as Sites 398 and 641, exhibit a persistent record (millions of years) of apparent dysoxic/anoxic conditions, that apparently peaked in the early Aptian, as recognized by subtle faunal and floral changes. It is not possible, given the presently-attained biostratigraphic resolution, to determine for certain whether the peak of the early Aptian OASE was narrowly synchronous on an ocean-wide scale, i.e., on the order of 0.5 m.y. or less, even though our data suggest that there may be some variability (Table 3).

Because precise correlation and stratigraphic resolution remains somewhat problematic, this interval may lie within almost any part of a second order eustatic cycle in the global sequence chronostratigraphy of Haq et al. (1987) and the Gulf of Mexico scheme of Scott et al. (1988). The condensed nature of the lower Aptian record, specifically the *Grantarhabdus coronadventis* nannofossil Subzone, in numerous sites would tend to indicate that it was deposited during a late transgressive interval (representing a "flooding surface") based on sequence stratigraphic principles (Vail et al., 1977; Loutit et al., 1988). If this is the

**TABLE 3**—Zonal positions of $C_{org}$-rich and associated horizons.

| Zone/subzone | 641C | 398D | 511 | 417D | 167 | 463 | 763B | VER | CIS | PIO | CER | 364 | 402A |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NC7 | Min | Peak | Peak | Min | Min | Min | Oxic | Min | Min | Min | Min | — | Peak |
| NC6B | Min | Peak |  | Peak |  | Min |  | Min | Min | Min | Min |  |  |
| NC6A | Peak | Min |  | — |  | Peak |  | Peak | Peak | Peak | Peak |  |  |
| NC6 (undiff.) |  |  | Peak |  | Peak |  | Peak |  |  |  |  | Peak | Min |
| NC5 | Min | Min | — | — | Min | — | — | Min | Min | Min | Min | — | — |

Peak = evidence of peak dysoxia/anoxia; Min. = evidence of minor dysoxia/anoxia; Oxic = no evidence of dysoxia/anoxia; — stratigraphic interval not recovered or undatable. NC6 (undiff.) refers to sections in which subzones cannot be differentiated. VER = Vergons; CIS = Cismon; PIO = Piobbico; CER = Gorgo a Cerbara. See text for criteria used to identify peak and minor dysoxia/anoxia.

case, then peak dysoxia/anoxia in the underlying *Conusphaera rothii* nannofossil Subzone would lie in a final phase of rapid sea level rise in an analogous manner to the Cenomanian/Turonian boundary OAE (Fig. 17). Ferry and Rubino (1989) correlated the lower Aptian "Goguel Level" in the Vocontian Trough to shallow-water sequences interpreted as representing a flooding surface near the base of Bedoulian marls equivalent to the 109 Ma event of Haq et al. (1987) (ca. 122 Ma in this paper). Similar correlations have been made independently by Weissert and Lini (1991). However, the relationship between sea level and the early Aptian OASE is far less clear than that for the Cenomanian/Turonian boundary OAE which can be correlated directly with sequence stratigraphy in sections of the Western Interior Basin (e.g., Kauffman, 1977; Weimer, 1984).

Although the correlation of the early Aptian OASE to sea level changes is tenuous, the timing of the event on a global basis is better established as the result of the biostratigraphic work presented in this paper. The combination of partially-related global forcing mechanisms caused the oceans to be susceptible to oxygen deficiency during the early Aptian OASE. These factors include elevated sea level, volcanism and high productivity (e.g. Bralower et al., 1993). We are intrigued by the apparent correspondence between the timing of a major tectonovolcanic event in the early Aptian and the peak of the OASE. Evidence connecting volcanism and oxygen deficiency exists in lower Aptian sequences in the Pacific Ocean basin. For example, highly tuffaceous lower Aptian limestones occur in DSDP Site 463 (e.g., Dean et al., 1981) and in ODP Site 807 drilled on Ontong Java Plateau (Tarduno et al., 1991). A revised compilation of data (Larson, 1991) indicates an abrupt increase in spreading rates and increased mid-plate volcanism on a global basis in the latest Barremian-early Aptian (ca. 125–120 Ma; Figs. 17, 18). This pulse of activity persisted until about 80 Ma (early Campanian), with the highest production of basaltic crust occurring from 120 to 100 Ma. The oceanic crustal production for this period is nearly double the average for the periods 80–0 and 150–125 Ma. This pulse in crustal production has been attributed to a mantle "superplume" and probably had major effects on oceanic and atmospheric chemistry. Tarduno et al. (1991) argued for an even more momentous volcanic event, calling for construction of the Ontong Java Plateau, among others in the Pacific, to have occurred over only 1–2 million years beginning about 120 Ma.

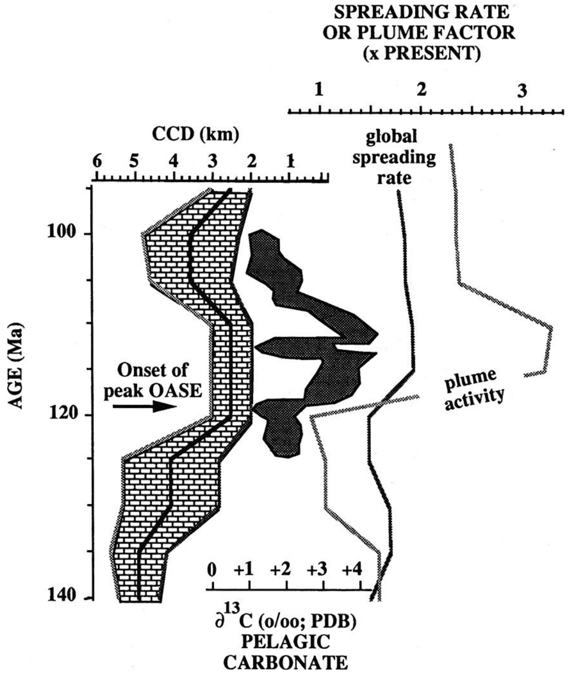

**FIGURE 18**—Early Cretaceous estimates for a) the Calcite Compensation Depth (CCD), b) carbon isotopic composition of pelagic carbonates, and c) the rate of ocean-floor basalt production by sea floor spreading and mid-plate plume activity. a) represents the mean and range (envelope) of the CCD at 5 million year intervals for the global ocean; b) the envelope of carbon isotopic values from 6 sequences analyzed in a companion study (Allard et al., in prep.); c) values for spreading rate factor and plume activity factor in present-day estimates based on Larson (1991).

This nearly instantaneous outpouring of basaltic lava associated with construction of Ontong Java and other oceanic plateaus, coincident with overall increase in seafloor spreading rate undoubtedly led to an increase in hydrothermal activity and overall thermal energy (heat flow), as well as an increase in outgassing of $CO_2$. Larson's (1991) scenario involves an increase of about 1.6 in world total basalt production in comparison to that of today. Assuming that this forced a proportional (linear) increase in rate of $CO_2$ outgassing associated with ridge, off-ridge, and island arc volcanism, then there would have been an increase of nearly $4.8 \times 10^{12}$ moles $CO_2$/y (assumed present rate of outgassing of $8 \times 10^{12}$ moles $CO_2$/y; Holland (1978)) with a carbon isotopic composition (assumed mantle as per Deines (1989) near −7‰). If the early Aptian $C_{org}$-preservation event was related to volcanism, how could the increase in basalt outpouring and $CO_2$ outgassing have induced dysoxia/anoxia and/or higher biologic productivity?

One explanation is to appeal to Vogt's (1989) concept of higher thermal energy and destabilization of the water column as the result of massive outpourings of basalt on the seafloor. Such a mechanism would mix nutrient-rich deep waters to the surface, promoting high productivity and higher $C_{org}$ fluxes to the seafloor. Initially, such a mechanism may have operated on relatively oxygen-depleted deep water masses rich in phosphate, and the higher $C_{org}$ fluxes, combined with dysaerobic to anaerobic conditions resulted in deposition of the $C_{org}$-rich sediments. Eventually, however, the nutrients would have been exhausted and deep water masses would have become oxygenated because of the enhanced oceanic turnover rates. This would lead to a transition from $C_{org}$-rich, chemically-reduced strata to more oxidized strata. It is interesting that oxidized, red-colored pelagic claystones and marlstones overlie the $C_{org}$-rich intervals in many lower Aptian sequences including North Atlantic sites (e.g., Site 417) and European sections (Vocontian Trough "placques rouges" and Cismon, Piobbico and other Italian sequences) (e.g., Arthur and Dean, 1986); we suggest that these beds might reflect the gradual stirring and oxidation following the $C_{org}$-burial event.

The ecological consequences of a rapid increase in upwelling and nutrient supply might also help to explain the low carbonate contents of $C_{org}$-rich horizons. Coccolithophores are adapted to relatively low nutrient concentrations (e.g., Margalef, 1978) and therefore might be excluded from widespread regions of oceanic turnover in high fertility. Dinoflagellates or other opportunists might have capitalized on the high nutrients, producing a sediment rich in $C_{org}$ but low in carbonate. Thus, it is not entirely clear whether, on the short-term, the early Aptian OASE represents mainly a carbonate-dissolution event, an ecologic event that excluded carbonate producers on the whole, or both. However, Figure 18 illustrates that on the long term this event was probably part of an overall rise to a higher CCD in the early Aptian (Thierstein, 1979). It is not yet clear whether the CCD rise was related directly to the volcanic event. The timing of the CCD rise is difficult to establish to 1 or 2 million year resolution. However, the rise could well have been a result of the volcanic event because one might expect a response to the rapid rate of $CO_2$ outgassing. This response might have involved an initial decrease in seawater pH with consequent increase in carbonate dissolution rate (e.g., add $CO_2$ without alkalinity). This in turn would have produced a short-term major CCD (and/or lysocline) rise. The overall CCD rise could account, in part, for the abrupt decrease in carbonate at base of the "Livello Selli" and equivalent $C_{org}$-rich horizons and ca. 0.5–1.0 million years of low carbonate. On the longer-term, $pCO_2$ may have continued to increase but increased rates of carbonate dissolution and terrestrial weathering would have returned alkalinity to oceans and lead to improved preservation of carbonate.

If paleoclimate models are correct, we should also see a significant global warming associated with the onset of volcanism and the OASE as the result of the $pCO_2$ increase, i.e., the rapid $CO_2$ outgassing may also have forced a global "greenhouse." The climatic "ultrathermal" of the last 150 million years occurred during the middle Cretaceous, primarily during the late Aptian through Albian. Increased $pCO_2$ has been suggested as one possible contributor to mid-Cretaceous warmth. Other possible causes probably played a subordinate role, as in the case of changing paleogeography (Barron, 1985), or possibly no important role at all, as in the case of oceanic heat transport in overall global warming (e.g., Covey and Barron, 1988). Results of general circulation models (GCM) for the Cretaceous (Barron and Washington, 1985) support a role for elevated $pCO_2$. Estimates for the $pCO_2$ of the mid-Cretaceous (centered on 110 Ma) range from 2 to about 13 times present levels on the basis of different criteria, including climate model studies, kinetic models linking ocean chemistry to tectonics, and interpretation of stable carbon isotope and other data (e.g., Berner et al., 1983; Lasaga et al., 1985; Berner, 1990; Arthur et al., 1991; Freeman and Hayes, 1992). There is some suggestion of a cooler Barremian and earliest Aptian (see Weissert (1989) for review) followed by significant warming, at least as reflected in the marine oxygen isotope record. The Early Cretaceous record (at least to the early Aptian) bears some evidence that high latitude (above 65° S) temperatures were seasonally subfreezing, producing periglacial winter "sea ice," ice-rafted detritus (Frakes and Francis, 1988) and isotopically-depleted precipitation typical of snow (Gregory et al., 1989; Rich et al., 1988) in parts of Australia. Glendonites, calcite replacements of ikaite (calcium-hexahydrite mineral) preferentially formed under freezing conditions in $C_{org}$ strata, have been found in sediments as young as late Aptian in the Arctic at 80° N (Kemper, 1987). There is little doubt that the Cretaceous as a whole cannot be lumped into the category of warm and equable (Frakes and Francis, 1990), but this further emphasizes the importance of the mid-Cretaceous "ultrathermal." Most workers agree that the Albian, and at least part of the Cenomanian, were the warmest part of the Cretaceous, but that high seasonality, cool polar climates probably did exist at that time (e.g., Crowley et al., 1986; Parrish and Spicer, 1988), and all GCM simulations produce ice on Antarctica, even with higher $pCO_2$ (4×) as a boundary condition (Barron and Washington, 1985; Schneider et al., 1985).

The warm global temperatures and probable high sea level stand also could have influenced oxygen solubility and ocean circulation and thereby the production and preservation of organic matter. For example, Cretaceous ocean GCM simulations by Barron and Peterson (1990) for a "high $pCO_2$" case produced stronger surface-water salinity gradients than those at present. Low-latitude regions in Tethys were characterized by model salinities that would have produced a sufficiently dense surface water mass to cause deep-water formation in that region of the ocean, particularly in northern hemisphere winter. The combination of transgression and flooding of low-latitude shelves with denser, more saline water masses may have induced more rapid overturn of the global ocean. A similar process was proposed for the Cenomanian/Turonian OAE by Arthur et al. (1987), who suggested that flooding of low-latitude evaporative marginal seas led to increased rates of "warm, saline" deep-water consequently driving upwelling of nutrients over large areas of the oceans, but particularly at ocean margins. Preliminary geochemical "box" models for the ocean suggest that this is one mechanism for promoting intermediate and deep-water dysoxia in the mid-Cretaceous oceans (Sarmiento et al., 1988). Formulation of this model such that one uses present-day parameters for exchange rates, preformed nutrients, river input, etc., but forms warm, saline bottom water (WSBW; Brass et al. (1982)) in low latitudes instead of cooler high-latitude sources, causes the average oxygen content of deep-water masses to fall to about 36 $\mu$mol $O_2$/kg instead of the present average of about 160 $\mu$mol/kg. An average value of dissolved $O_2$ of 36 $\mu$mol/kg suggests that much of the bottom-water mass probably was anoxic ($<10$ $\mu$mol/kg). However, using a model modern thermohaline circulation, ocean deep-water masses can also be made to go anoxic by increasing deep-water residence times by a factor of 2–10 (e.g., Wilde and Berry, 1982; Bralower and Thierstein, 1984), depending on the turnover rate of the intermediate water mass. Thus, widespread deeper-water anoxia can result from average surface-ocean productivities lower than the present with a warmer deep ocean and lower initial oxygen solubility. While the record indicates that this mechanism operated for long intervals of time in the mid-Cretaceous, for shorter duration events such as the early Aptian OASE, we favor a mechanism that increases overturn and productivity while decreasing oxygen solubility as described above.

As in the case of the Cenomanian/Turonian OAE, a global carbon isotope excursion also appears to be closely related to the early Aptian OASE (e.g., Weissert et al., 1985 (S. Alps); Weissert and Bréhéret, 1991 (Fosse Vocontien); Allard et al., in prep. (central Pacific DSDP sites)). However the major positive carbon isotope excursion occurred in the late stages of the OASE (e.g., Weissert and Lini, 1991) (Fig. 18) rather than in conjunction with the main phase as manifested by the Selli Level and $C_{org}$-rich equivalents. It remains a major challenge to tie these events together into a coherent model that relates to the possibly major driving force of global change in the early to middle Aptian globally widespread volcanism, but we offer a tentative model below.

If the OASE was characterized by increased organic carbon burial rates relative to carbonate burial (e.g., the $C_{org}/CaCO_3$ ratio increased), we would expect the carbon isotopic composition of the oceanic dissolved carbonate reservoir to increase (see Arthur et al. (1987), (1988) for explanation related to the Cenomanian/Turonian event); this would, in turn, be reflected in a positive excursion in the carbon isotopic composition of pelagic carbonate components. Because the positive excursion appears to have been delayed by at least 0.5–1.0 million years, relative to the beginning of the OASE as reflected in the Selli Level, and lasted well beyond the timing of the OASE (into the early Albian), we must consider why the carbon system did not respond to the presumed global increase in $C_{org}$ burial associated with the OASE. An obvious possibility is that there was no global increase in $C_{org}$-burial rates. We cannot directly counter that argument because of the lack of good accumulation rate estimates; however, we consider it likely that $C_{org}$-burial rates did increase. If we assume that this was the case, how can we resolve the lack of response?

One way is to consider the increased rate of isotopically light "mantle" $CO_2$ to the atmosphere/ocean; this rate may have been high enough to counteract the effect of increased rates of $C_{org}$ burial on the isotopic composition of the oceanic DIC reservoir. Thus, this situation would have initially promoted lower or relatively constant carbonate $\delta^{13}C$, relative to an expected positive excursion with increased rates of $C_{org}$ burial (but without excess $CO_2$ addition), and the positive carbon isotopic excursion would have been delayed somewhat even though $C_{org}$-burial rates are inferred to have risen within $C_{org}$-rich horizons. The main $\delta^{13}C$ excursion in both carbonate and $C_{org}$ occurs just above the Selli (Allard et al., in prep.), probably within 0.5 to 1.0 m.y. $CO_2$ injection also will increase ($CO_2$aq) and decrease DIC$\delta^{13}C$, assuming that the $CO_2$ is mantle carbon with $\delta^{13}C$ of ca. $-7‰$. Increased ($CO_2$aq) would perhaps have led to decreased $\delta^{13}C_{org}$ (e.g., Arthur et al., 1988; Popp et al., 1989; Rau et al., 1989, 1991; Freeman and Hayes, 1992). This would perhaps explain the decreased $\delta^{13}C_{org}$ values in the Selli Level (like the Toarcian event of Jenkyns and Clayton (1986) and Jenkyns (1988)) when we would have expected heavier values as the result of high productivity and increased rates of $C_{org}$ burial as observed in the Cenomanian/Turonian case (Arthur et al., 1988). The isotopic composition of the $C_{org}$ would have risen after the initial event, along with that of carbonate, as the result of the addition of alkalinity, rise in pH, decrease in ($CO_2$aq) and consequent increase in the $\delta^{13}C_{org}$ and leveling off of the rate of addition of volcanic $CO_2$.

Such a model cannot, however, explain the rapid increase in the $\delta^{13}C$ of the oceanic carbon reservoir in the later stages of the early Aptian OASE. There are at least two possibilities: 1) that oceanic stability increased again, resulting in strong carbon isotopic gradients and $^{13}C$-enriched surface waters; or 2) that more rapid $C_{org}$ burial occurred elsewhere in the oceans (e.g., on shelves or in deltas) or on land ($CO_2$ fertilized terrestrial plant communities that developed major coal deposits).

As is obvious from the above discussion, there are many fruitful lines of investigation into the paleoceanography of this major episode of global change in the late Barremian-early Aptian that remain to be carefully researched and elucidated. Testing of all of the hypotheses will depend, however, on availability of an adequate stratigraphic framework such as that developed in some sections here. Clearly both the biostratigraphy and paleoceanographic models still need further refinement.

## SUMMARY AND CONCLUSIONS

1) We have conducted an integrated biostratigraphic, lithostratigraphic and geochemical investigation of fourteen upper Barremian-lower Aptian sections deposited in a range of geographic and oceanographic settings. We conclude that the early Aptian was marked by the occurrence of a brief interval of dysoxic/anoxic conditions on a global scale and call this interval the early Aptian Oceanic Anoxic Sub Event (OASE). This OASE can be recognized in different sites from a combination of lithostratigraphic and micropaleontologic evidence. These include the presence of laminated sediments, relatively high organic carbon contents and calcareous plankton-free intervals.
2) Integrated foraminiferal and nannofossil stratigraphy indicates that most locations were characterized by a relatively brief interval of peak dysoxia/anoxia (<1 m.y.) within a longer interval (2–3 m.y.) of intermittent oxygen deficiency which began in the latest Barremian. In many sites, this peak lies within the *Globigerinelloides blowi* foraminiferal Zone (regardless of its chronostratigraphic assignment) and the *Chiastozygus litterarius* nannofossil Zone (*Conusphaera rothii* Subzone), shortly above magnetic Chronozone M0. The timing of this peak does appear to be slightly variable.
3) Nannofossil assemblage data indicate highly variable fertility during the late Barremian-early Aptian. While peak oxygen deficiency appears to have corresponded to a highly eutrophic interval, less intense dysoxic/anoxic periods were characterized by oligotrophic conditions. The late Barremian-early Aptian is characterized by a broad interval of radiation in both the planktonic foraminifers and calcareous nannofossils. However, the OASE is not directly associated with evolutionary radiations in either group. The time-transgressive extinction of *Nannoconus steinmannii* may be associated with events leading to oxygen deficiency such as periodically eutrophic surface waters.
4) Tectonovolcanic events such as increased production of mid-plate oceanic curst may have indirectly induced the dysoxic/anoxic episode by causing complex changes in climate, ocean chemistry and circulation, and sea level. The complexity of these inter-relationships, however, is demonstrated by the lack of a clear stratigraphic relationship between $C_{org}$-rich horizons and the carbon isotopic record.

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## APPENDIX I: CALCAREOUS NANNOFOSSIL TAXONOMY

*Hayesites albeinsis* Manivit, 1971. This species has been observed in one sample (641C-7R-1, 42–43 cm) which is below its normal range. There is no certain explanation of this occurrence.

*Parhabdolithus achlyostaurion* Hill, 1976

*Corollithion achylosum* (Stover, 1966) Thierstein, 1971. Fig. 19.29–30. In the middle-upper Barremian of Holes 641C and 398D, we have observed some very small (3–4 μm diameter) specimens which possess a similar shield structure to typical *C. achylosum* but have relatively wider cross-bars, sometimes almost entirely filling the central area (e.g., Fig. 19.31, 32). The size of these forms increases through the upper Barremian. Since we have not observed this form in the SEM, we classify it as *C.* cf. *C. achylosum.* We have not seen any forms similar to the holotype in the Barremian and lowermost Aptian of Holes 398D and 641C.

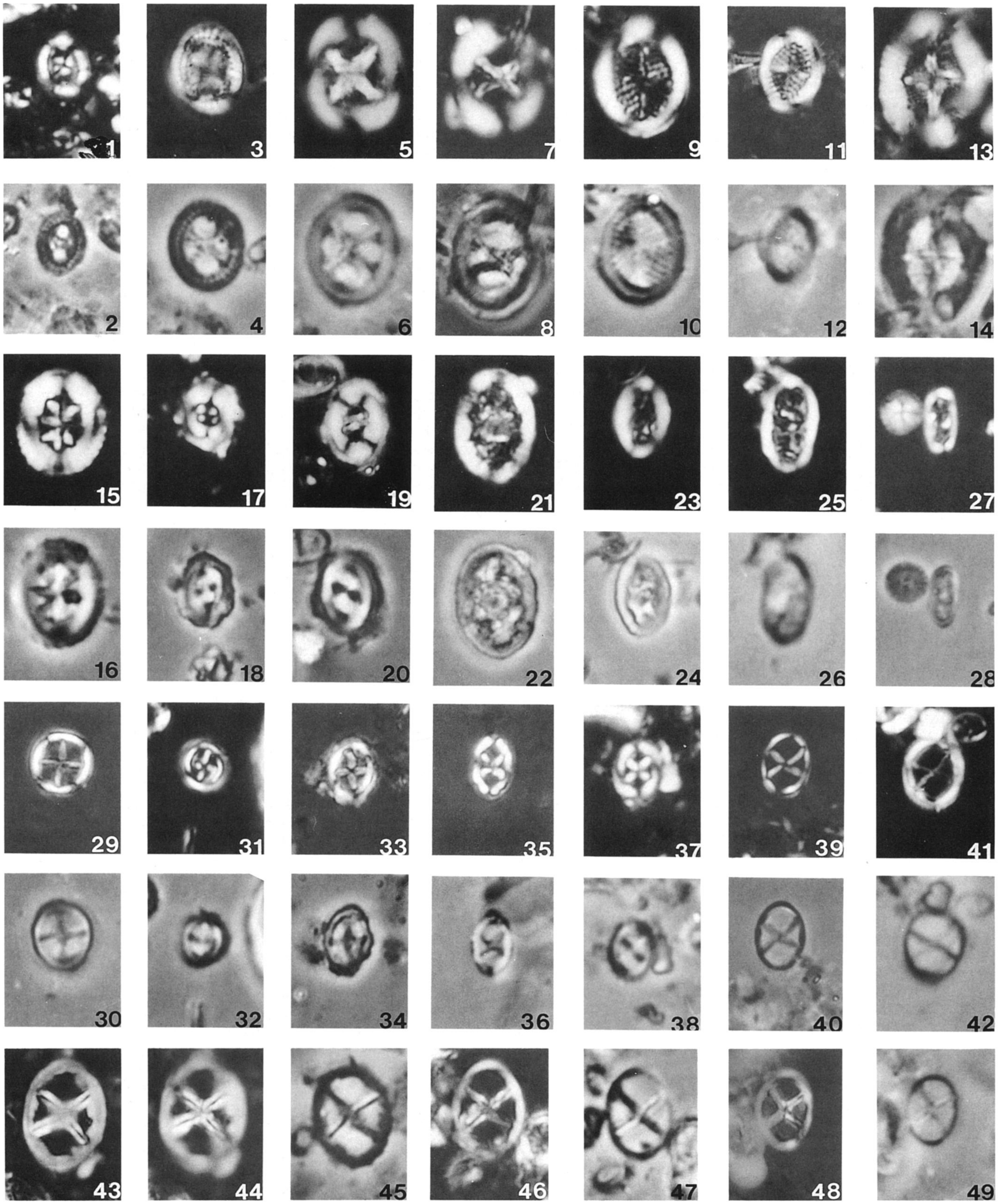
*Corollithion acutum* Thierstein in Roth and Thierstein, 1972. Fig. 19.41, 42; Fig. 21.1, 2, 5. Some specimens of *Corollithion* in the upper Barremian of Hole 398D are similar to *C. acutum* but have a larger (45–90°) angle between the cross bars (Fig. 19.39, 40). Specimens observed in the same interval of Hole 641C, also contain a high angle between cross-bars, but have a different shield structure from typical *C. acutum,* possessing a much wider inner cycle (e.g., Fig. 19.35–38; Fig. 21.3, 4). Both of these variations are grouped under *C.* cf. *C. acutum.* Typical specimens of *C. acutum* appear very suddenly in the lowermost Aptian of both holes, and provide a good biostratigraphic marker.

*Lithraphidites alatus* ssp. *magnus* Covington and Wise, 1987. Fig. 20.7, 8.

*Bukrylithus ambiguus* Black, 1971

*Cretarhabdus angustiforatus* (Black, 1971) Bukry, 1973. Fig. 19.15, 16. The last occurrence of forms with wide central areas occurs in the lower Aptian. Rare forms with much narrower central areas, which appear to be related to *C. octofenestratus* Bralower (in Bralower et al., 1989), are found higher in the Cretaceous (e.g., Bralower, 1988). This difference needs more detailed biometric study.

*Parhabdolithus angustus* (Stradner, 1963) Stradner, Adimaker & Maresch, 1968 emended Bralower, Erba and Mutterlose. Fig. 19.27, 28; Fig. 22.13. The holotype of this species is a drawing (Stradner, 1963) with a length/width ratio of approximately 2.6. Stradner et al. (1968) provided a more detailed description and included a hypotype (TEM) with a length/width of 1.64. They also published several light micrographs with length/width ratios close to 2. There have been little morphometric data given for this species and no differential diagnosis between it and *Parhabdolithus splendens.* The upper Barremian/lower Aptian section at Sites 398 and 641 show gradational forms between *P. angustus* and *P. splendens.* In Core 641C-10R, we observed a few extremely small intermediate forms which possess a well-developed central process but lack granular elements in the central area (transitional with *Z. pseudoangustus*). In the upper Barremian of both Sites 398 and 641, numerous elongate specimens with length/width ratios typical of *P. angustus* lacked the typical parallel sides (transitional with *P.*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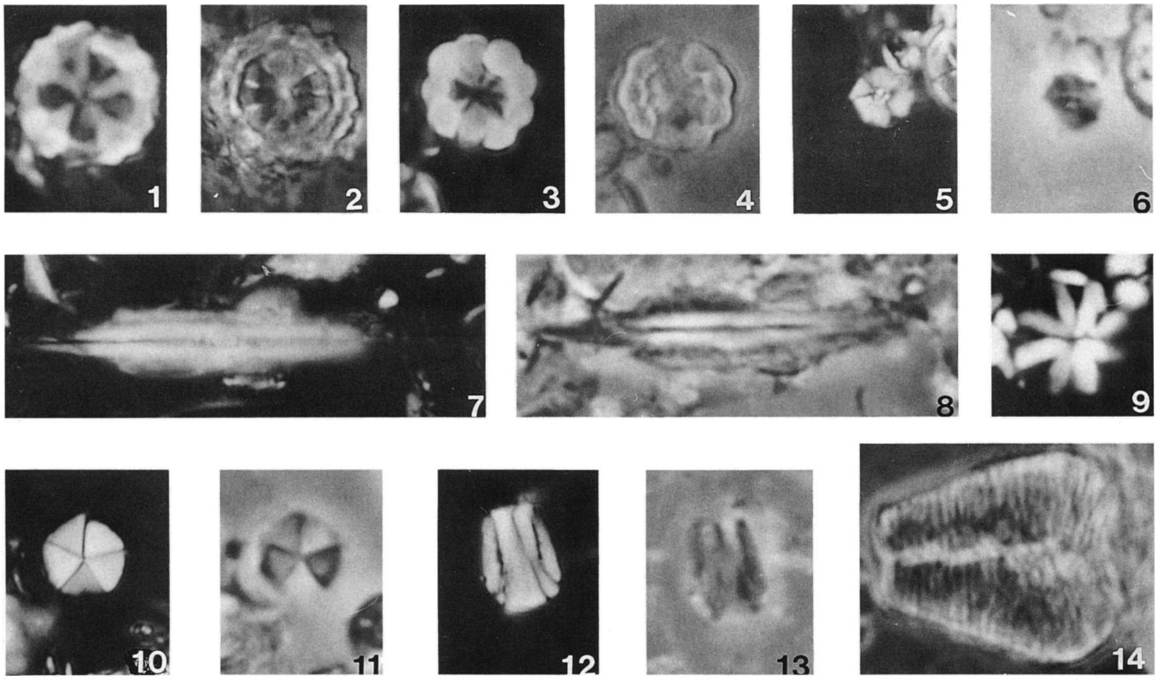

**FIGURE 20**—Light micrographs of calcareous nannofossils discussed. **1–4:** *Eprolithus floralis,* 1, 2: ODP 641C-8R-2, 8–10 cm; 3, 4: DSDP 418B-33-1, 107–108 cm; **5, 6:** *Rucinolithus irregularis,* ODP 641C-11R-1, 58–59 cm; **7, 8:** *Lithraphidites alatus* ssp. *magnus,* DSDP 398D-129-1, 125–127 cm; **9:** *Hayesites radiatus,* ODP 641C-8R-4, 126–127 cm; **10, 11:** *Micrantholithus hoschulzii,* DSDP 398D-122-3, 41–42 cm; **12, 13:** *Conusphaera rothii,* DSDP 398D-122-3, 41–42 cm; **14:** *Nannoconus steinmannii,* ODP 641C-9R-3, 134–135 cm. All micrographs are ×2450.

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**FIGURE 19**—Light micrographs of calcareous nannofossils discussed. **1, 2:** *Hemipodorhabdus gorkae*; DSDP 511-58-2, 93–94 cm. **3, 4:** *Axopodorhabdus decorus*; DSDP 547A-60-3, 108–109 cm. **5,6:** *Grantarhabdus coronadventis*; ODP 641C-1-3, 88–89 cm. **7, 8:** *Grantarhabdus meddii*; DSDP 511-58-2, 93–94 cm. **9–12:** *Cretarhabdus loriei*; 9, 10: ODP 641C-10R-6, 13–14 cm, 11, 12: DSDP 398D-129-1, 125–127 cm. **13, 14:** *Miravetesina favula*; DSDP 398D-125-5, 113–115 cm. **15, 16:** *Cretarhabdus angustiforatus*; ODP 641C-10R-1, 15–16 cm. **17–20:** *Flabellites oblongus*; 17, 18: DSDP 364-42-5, 148–149 cm; 19, 20: DSDP 545-46-4, 53–54 cm. **21, 22:** *Parhabdolithus asper*; ODP 641C-10R-3, 112–113 cm. **23–26:** *Parhabdolithus splendens*; 23, 24: DSDP 417D-21-3, 13–14 cm; 25, 26: ODP 641C-11R-4, 95–96 cm. **27, 28:** *Parhabdolithus angustus*; DSDP 417D-21-4, 28–29 cm. **29, 30:** *Corollithion achylosum*; DSDP 511-55-1, 139–140 cm. **31, 32:** *Corollithion* cf. *C. achylosum*; ODP 641C-10R-1, 15–16 cm. **33, 34:** *Corollithion* sp.: DSDP 547A-57-5, 81–82 cm. **35–40:** *Corollithion* cf. *C. acutum*; 35, 36: ODP 641C-10R-6, 13–14 cm; 37, 38: ODP 641C-13R-2, 27–28 cm; 39, 40: DSDP 398D-125-6, 64–65 cm. **41, 42:** *Corollithion acutum*; ODP 641C-10R-1, 15–16 cm. **43–47:** *Chiastozygus litterarius,* 43-45: DSDP 547A-60-5, 45–46 cm; 46, 47: ODP 641C-11R-5, 8–9 cm; **48, 49:** *Chiastozygus* sp., DSDP 398D-129-1, 125–127 cm. All micrographs are ×2450.

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**FIGURE 21**—Scanning electron micrographs of calcareous nannofossils discussed. **1:** *Corollithion acutum,* distal view DSDP 417D-21-4, 28–29 cm; **2:** *Corollithion acutum,* proximal view, DSDP 418A-15-1, 8–9 cm; **3, 4:** *Corollithion* cf. *C. acutum,* distal view, DSDP 603B-44-2, 100–102 cm; **5:** *Corollithion acutum,* oblique view, DSDP 417D-21-4, 28–29 cm; **6, 7:** *Corollithion geometricum,* distal view, ODP 641C-10R-1, 135–136 cm. **8:** *Corollithion geometricum,* proximal view, DSDP 417D-21-4, 28–29 cm; **9:** *Prediscosphaera* cf. *P. columnata,* distal view, DSDP 364-41-4, 11–12 cm; **10:** *Rotelapillus laffittei,* DSDP 418A-15-1, 8–9 cm. **11:** *Flabellites oblongus,* distal view, DSDP 418A-15-1, 8–9 cm; **12:** *Prediscosphaera* cf. *P. columnata,* proximal view, DSDP 364-41-4, 11–12 cm; **13:** Coccolithophore of *Watznaueria barnesae,* DSDP 418A-15-1, 8–9 cm; **14:** *Flabellites oblongus,* proximal view, DSDP 417D-12-1, 28–29 cm. White scale bar on each micrograph represents 1 μm.

**FIGURE 22**—Scanning electron micrographs of calcareous nannofossils discussed. **1–5:** *Parhabdolithus asper:* 1, 2: distal view; 1. DSDP 603B-44-1, 120–122 cm; 2. DSDP 100-1-1, 13–14 cm; 3, 4: oblique proximal views; 3, DSDP 603B-44-1, 120–122 cm; 4. DSDP 100-1-1, 13–14 cm. 5. distal view, ODP 641C-10R-1, 135–136 cm. **6–12:** *Parhabdolithus splendens:* 6, proximal view, DSDP 418A-15-1, 8–9 cm; 7–12: distal views; 7. ODP 641C-10R-1, 135–136 cm; 8. DSDP 418A-15-1, 8–9 cm; 9. DSDP 418A-15-1, 8–9 cm; 10. ODP 641C-10R-1, 135–136 cm; 11. DSDP 364-41-4, 11–12 cm; 12. DSDP 418A-15-1, 8–9 cm. **13:** *Parhabdolithus angustus,* proximal view, DSDP 418A-15-1, 8–9 cm. **14:** *Zeugrhabdotus pseudoangustus,* DSDP 418A-15-1, 8–9 cm. **15:** *Parhabdolithus* cf. *P. infinitus,* ODP 641C-10R-1, 135–136 cm, distal view. **16:** *Parhabdolithus infinitus,* distal view, DSDP 603B-44-2, 100–102 cm. White scale bar on each micrograph represents 1 μm.

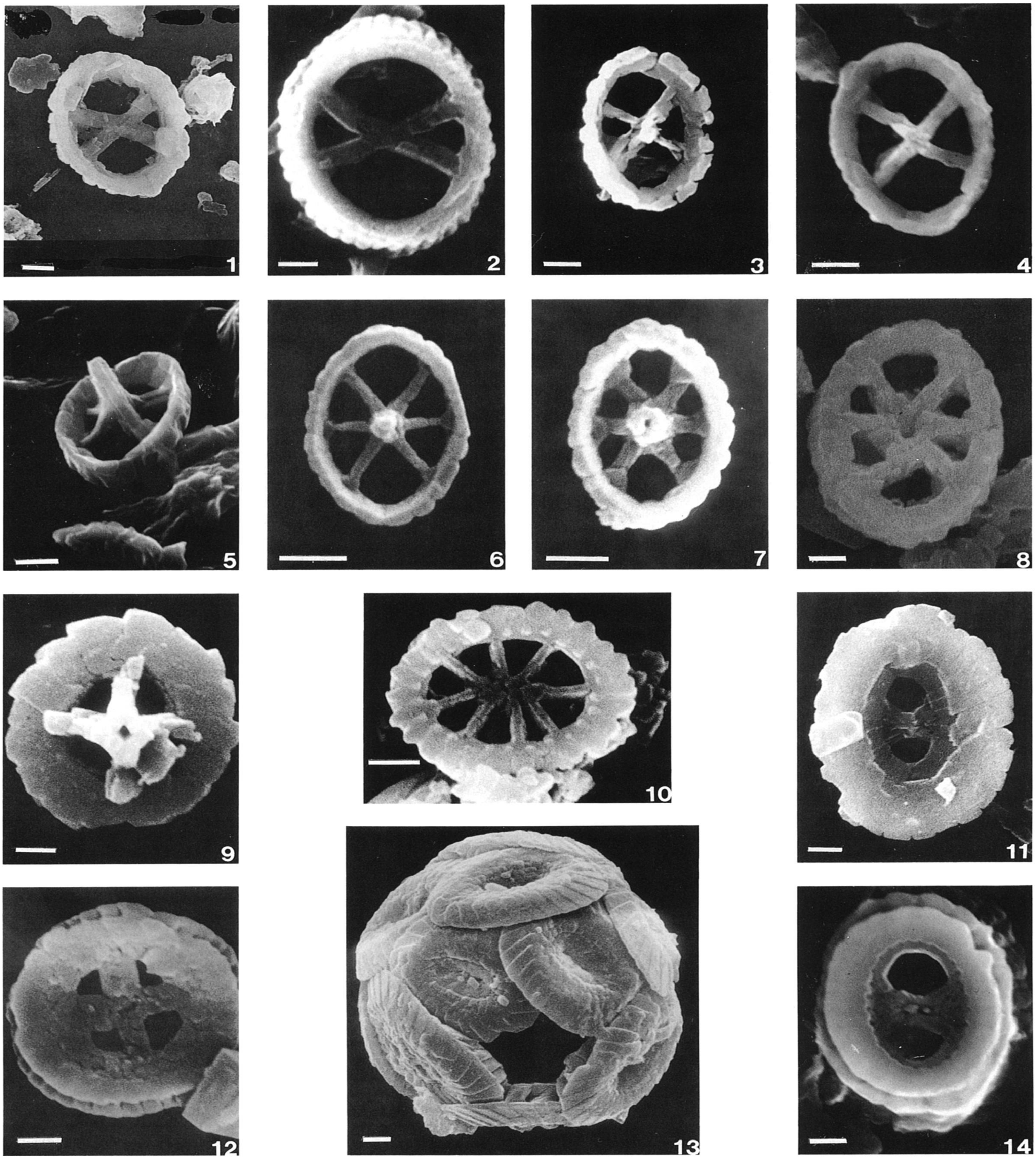

FIGURE 21.

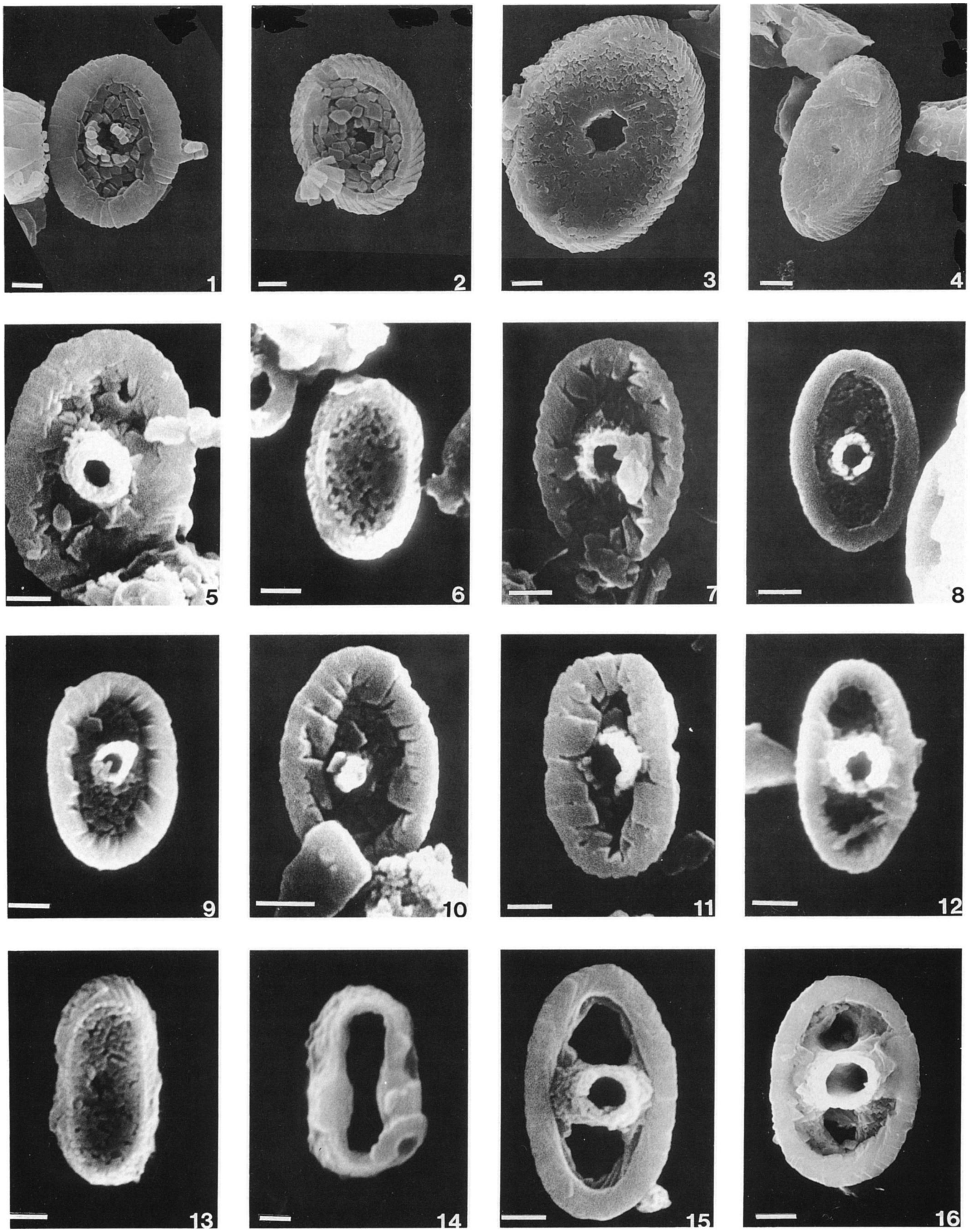

**FIGURE 22.**

*splendens*). These intermediate forms reduce the certainty with which the true first occurrence of *P. angustus* can be determined. We have analyzed numerous published photomicrographs of the species *P. angustus*, *P. asper* and *P. splendens* and have found that most specimens cluster into three length/width ratio ranges: 1.25–1.45 (usually termed *P. asper*), 1.55–1.85 (usually assigned to *P. splendens*) and 2.0–2.2 (usually classified as *P. angustus*). Based on these analyses, we make the following formal emendation of *P. angustus*. Note that we would include the hypotype of Stradner et al. (1968) in *P. splendens*.

Emendation *Parhabdolithus angustus* possesses parallel sides, a granular central area and has a length/width ratio of greater than 2.

Differential diagnosis: *Parhabdolithus splendens* has a length/width ratio of less than 2 (usually between 1.55 and 1.85). We also include in this taxon specimens with a length/width ratio greater than 2, but with non-parallel sides. *Zeugrhabdotus pseudoangustus* usually has a length/width ratio greater than 2, but has a non-granular central area with a prominent central process.

*Parhabdolithus asper* (Stradner, 1963) Manivit, 1971. Fig. 19.21, 22; Fig. 22.1–5. See discussion of *P. angustus*.

*Watznaueria barnesae* (Black, 1959) Perch-Nielsen, 1968. Fig. 21.13.

*Nannoconus bermudezii* Brönnimann, 1955

*Watznaueria biporta* Bukry, 1969

*Watznaueria britannica* (Stradner, 1963) Reinhardt, 1964

*Amphizygus brooksii* Bukry, 1969

*Nannoconus bucheri* Brönnimann, 1955

*Lithraphidites carniolensis* Deflandre, 1963

*Microstaurus chiastius* (Worsley, 1971) Bralower et al., 1989

*Markalius circumradiatus* (Stover, 1966) Perch-Nielsen, 1968

*Speetonia colligata* Black, 1971

*Prediscosphaera columnata* (Stover, 1966) Perch-Nielsen, 1984. Fig. 21.9, 12. We may have observed the very earliest forms of this taxon at DSDP Site 364. These have a distinctly different appearance in the light microscope having a light gray outer shield. In the SEM, the distal shield (Fig. 21.9) appears to be very similar to *P. columnata*. The proximal shield appears more complex (Fig. 21.12) with additional cycles of elements. The proximal side of the cross also looks more complex, constructed of several rows of elements. Because of these differences, we have included these forms in *P.* cf. *P. columnata*.

*Watznaueria communis* Reinhardt, 1964

*Cretarhabdus conicus* Bramlette & Martini, 1964

*Biscutum constans* (Gorka, 1957) Black ex Black & Barnes, 1959

*Tetrapodorhabdus coptensis* Black, 1971. See comments for *A. decorus*.

*Grantarhabdus coronadventis* (Reinhardt, 1966) Grün *in* Grün and Allemann, 1975. Fig. 19.5, 6. Investigation of the upper Barremian-lower Aptian section at Site 641 indicates that this species is a descendant of *Grantarhabdus meddii* Black, 1971. The definitions of these species do not give a differential diagnosis; we use one that conforms with both holotypes: the angle between cross-bars in *G. meddii* is acute, whereas that in *G. coronadventis* is equal to or greater than 90°.

*Prediscosphaera cretacea* (Arkhangelsky, 1912) Gartner, 1968

*Cruciellipsis cuvillieri* (Manivit, 1966) Thierstein, 1971

*Axopodorhabdus decorus* (Deflandre, 1954) Wind and Wise *in* Wise and Wind, 1977. Fig. 19.3, 4. This species is an end-member of the *Hemipodorhabdus gorkae-Tetrapodorhabdus coptensis* lineage as described by Grün and Allemann (1975) and we have applied their proposed characteristics to differentiate these three species. We use *A. decorus* instead of the junior synonym *Tetrapodorhabdus granulatus* (Reinhardt, 1965). Very few specimens of true *T. coptensis* were observed in this investigation. A rapid evolutionary transition from *H. gorkae* to *A. decorus* can be observed in the lower Aptian section of Site 641 and includes an increase in size from 4 μm to 8 μm as well as a change in the construction of the cross.

*Axopodorhabdus dietzmannii* (Reinhardt, 1965) Wind & Wise *in* Wise & Wind, 1977

*Zygodiscus diplogrammus* (Deflandre & Fert, 1954) Gartner, 1968

*Zygodiscus elegans* (Gartner, 1968) Bukry, 1969

*Corollithion ellipticum* Bukry, 1969

*Nannoconus elongatus* Brönnimann, 1955

*Parhabdolithus embergeri* (Noël, 1959) Bralower, Monechi & Thierstein, 1989

*Zygodiscus erectus* (Deflandre, 1954) Bralower, Monechi & Thierstein, 1989

*Miravetesina favula* Grün in Grün and Allemann, 1975. Fig. 19.13, 14. Our concepts for this species are described in Bralower et al. (1989).

*Percivalia fenestrata* (Worsley, 1971) Wise, 1983

*Zygodiscus fissus* (Grün and Zweili, 1980) Roth, 1983

*Eprolithus floralis* (Stradner, 1962) Stover, 1966. Fig. 20.1–4. We do not differentiate between various precursor forms of *E. floralis* (e.g., Mutterlose and Wise, 1990) because they cannot be distinguished in poorly preserved material. See comments under *Eprolithus* sp.

*Scapholithus fossilis* Deflandre in Deflandre and Fert, 1954

*Pickelhaube furtiva* (Roth, 1983) Applegate, Covington & Wise, 1987

*Tranolithus gabalus* Stover, 1966

*Corollithion geometricum* (Gorka, 1959) Manivit, 1971. Fig. 21.6–8.

*Nannoconus globulus* (Brönnimann, 1955) subsp. *globulus*

*Hemipodorhabdus gorkae* (Reinhardt, 1969) Grün & Allemann, 1975. Fig. 19.1, 2. See comments for *A. decorus*.

*Ethmorhabdus hauterivianus* Covington and Wise, 1987

*Sollasites horticus* (Stradner et al., 1966) Cepek and Hay, 1969

*Micrantholithus hoschulzii* (Reinhardt, 1966) Thierstein, 1971. Fig. 20.10, 11.

*Parhabdolithus infinitus* (Worsley, 1971) Thierstein, 1972. Fig. 22.16. In the SEM, we observed a specimen (Fig. 22.15) which is much narrower than typical *P. infinitus* and has a reduced floor in the central area, but is otherwise similar. Pending further investigation, we classified this as *P.* cf. *P. infinitus*.

*Assipetra infracretacea* (Thierstein, 1973) Roth, 1973

*Rucinolithus irregularis* Thierstein in Roth and Thierstein, 1972. Fig. 20.5, 6.

*Nannoconus kamptneri* (Brönnimann, 1955) subsp. *kamptneri*

*Rotelapillus laffittei* (Noël, 1956) Noël, 1973. Fig. 21.10.

*Diazomatolithus lehmanii* Noël, 1965

*Chiastozygus litterarius* (Gorka, 1957) Manivit, 1971. (Fig. 19.43–47). This study confirms the conclusion of Bralower (1990) that true specimens of *Chiastozygus litterarius*, which possess a sturdy cross whose bars appear split in cross-polarized light, are only observed below the Aptian in well-preserved material from North Atlantic DSDP sites (e.g., Sites 398 and 641). However, in moderately- and poorly-preserved material from other DSDP sites and sequences in Southern France and Italy, such morphotypes appear in the lowermost Aptian close to the first occurrence of *Rucinolithus irregularis* (e.g., Thierstein, 1973; Roth, 1983; Bralower, 1987). We classify specimens without a sturdy cross in *Chiastozygus* sp. (e.g., Fig. 19.48, 49).

*Cretarhabdus loriei* Gartner, 1968. Fig. 19.9–12.

*Octocyclus magnus* Black, 1972

*Tetralithus malticus* Roth, 1973

*Cyclagelosphaera margerelii* Noël, 1965

*Vagalapilla matalosa* (Stover, 1966) Thierstein, 1973. This species is observed in the Valanginian of ODP Site 766 (Mutterlose, in press) and therefore is not a good lower Aptian marker as previously suggested.

*Grantarhabdus meddii* Black, 1971. Fig. 19.7, 8. See remarks for *G. coronadventis*.

*Conusphaera mexicana* (Trejo, 1969) subsp. *mexicana*

*Nannoconus minutus* Brönnimann, 1955

*Vagalapilla mutterlosei* Crux, 1989

*Calcicalathina oblongata* (Worsley, 1971) Thierstein, 1971

*Flabellites oblongus* (Thierstein, 1973) Crux, 1982. Fig. 19.17–20; Fig.

21.11, 14. This species arises in the late Barremian. Early morphotypes contain a very narrow angle between the cross-bars and a reduced central area. This angle gradually increases through time.

*Micrantholithus obtusus* Stradner, 1963

*Broinsonia orthocancellata* Bukry, 1969

*Watznaueria ovata* Bukry, 1969

*Rhabdolekiskus parallelus* Wind & Cepek, 1979

*Repagulum parvidentatum* (Deflandre and Fert, 1954) Forchheimer, 1972

*Manivitella pemmatoidea* (Deflandre ex Manivit, 1965) Thierstein, 1971

*Diloma placinum* Wind and Cepek, 1979

*Zeugrhabdotus pseudoangustus* Bralower et al. *in* Covington & Wise, 1987. Fig. 22.14.

*Hayesites radiatus* (Worsley, 1971) Thierstein, 1976. Fig. 20.9.

*Diadorhombus rectus* Worsely, 1971.

*Braarudosphaera regularis* Black, 1973

*Discorhabdus rotatorius* (Bukry, 1969) Thierstein, 1973

*Conusphaera rothii* (Thierstein, 1971) Jakubowski, 1986. Fig. 20.12, 13.

*Crucibiscutum salebrosum* (Black, 1971) Jakubowski, 1987

*Cretarhabdus schizobrachiatus* (Gartner, 1968) Bukry, 1969

*Corollithion silvaradion* Filewicz, Wind and Wise *in* Wise and Wind, 1977

*Prediscosphaera spinosa* (Bramlette and Martini, 1964) Gartner, 1968

*Parhabdolithus splendens* (Deflandre, 1953) Noël, 1969. Fig. 19.23–26; Fig. 22.6–12. See discussion of *P. angustus*.

*Nannoconus steinmannii* (Kamptner, 1931) subsp. *steinmannii*. Fig. 20.14. We combine this species with *N. colomii* as it is not always possible to discern a central cavity.

*Tegumentum stradneri* Thierstein *in* Roth & Thierstein, 1972

*Vagalapilla stradneri* (Rood, Hay & Barnard, 1971) Thierstein, 1973

*Crucicribrum striatum* subsp. *constansii* Wise and Parker *in* Wise, 1983

*Tegumentum striatum* (Black, 1971) Taylor, 1979

*Cretarhabdus surirellus* (Deflandre, 1954) Reinhardt, 1970

*Rucinolithus terebrodentarius* Applegate et al. *in* Covington & Wise, 1987

*Nannoconus truittii* Brönnimann, 1955

*Chiastozygus* sp. Fig. 19.48, 49. We have used this term for those specimens of *Chiastozygus* with narrow, delicate bars (see discussion of *C. litterarius*).

*Eprolithus* sp. Numerous specimens of forms clearly transitional between *Eprolithus* and *Rucinolithus* have been seen in the lower Aptian of several DSDP Sites. In these forms, some elements appear imbricated while others appear non-imbricated. The number of elements varies between 9 and 15.

*Lapideacassis* sp.

*Thoracosphaera* sp. Several small pieces of *Thoracosphaera* have been observed which cannot be assigned to an individual species.

*Zebrashapka* sp.

*Zygodiscus* sp.

## APPENDIX II:
## NEW LOWER APTIAN NANNOFOSSIL SUBZONES

### *Conusphaera rothii* Subzone (NC6A)

Definition: Interval from the first occurrence of *Rucinolithus irregularis* Thierstein to the last occurrence of *Conusphaera rothii* (Thierstein).

Authors: Bralower et al., this study.

Remarks: We include *Conusphaera mexicana* subsp. *mexicana* in the species concept of *C. rothii.* There has been much discussion on potential differences between these taxa (e.g., Bralower et al., 1989). Regardless of morphological variation, the upper range of both taxa appears to be similar, however, we use *C. rothii* for the name and definition of this subzone as this form is more commonly found in this interval. Nannofossil first occurrences in this subzone include those of *Grantarhabdus coronadventis* and *Corollithion achylosum.* This subzone correlates with magnetic polarity zone MO and with the peak of the early Aptian OASE. The abbreviation for this subzone (NC6A) is adapted from the zonal abbreviation scheme of Roth (1978).

Reference Sections: This interval is observed in numerous sites studied, but can be best defined at DSDP Site 398 (Sections 398D-123-3 to -120-4) and ODP Site 641 (Sections 641C-11R-1 to 8R-5).

Known Range: basal Aptian.

### *Grantarhabdus coronadventis* Subzone (NC6B)

Definition: Interval from the last occurrence of *Conusphaera rothii* (Thierstein) to the first occurrence of *Eprolithus floralis* (Stradner).

Authors: Bralower et al., this study.

Remarks: Extinctions in this interval include those of *Cretarhabdus angustiforatus* and *Nannoconus steinmannii.* This is a very condensed interval in all sections observed with the exception of Hole 398D. There is a distinct possibility of an unconformity in this subzone in Hole 641C. The abbreviation for this subzone (NC6B) is adapted from the zonal abbreviation scheme of Roth (1978).

Reference Sections: This narrow interval is best defined at DSDP Site 398 (Sections 398D-120-4 to -118-5) and ODP Site 641 (Sections 641C-8R-5 to -8R-3).

Known Range: upper lower Aptian.