AN INTEGRATED CRETACEOUS MICROFOSSIL BIOSTRATIGRAPHY

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ABSTRACT: We have constructed an integrated calcareous nannoplankton, calpionellid, and planktonic foraminifer biostratigraphy for the Cretaceous Period. This biostratigraphy, which consists of 73 informal zones, is based upon a literature survey of numerous DSDP/ODP and land sections as well as our own investigation of several of these sequences. Although the sections included are from low, mid, and high latitudes, from all of the major ocean basins and from epicontinental seaways, the integrated scheme is most applicable in mid- and low-latitude sequences. Current nannofossil, calpionellid, and planktonic foraminiferal zonations offer limited resolution (2–6 my/zone) in the Cretaceous Period. The integrated zonation scheme proposed significantly increases potential biostratigraphic resolution to between 0.5 and 1.5 my/zone because these fossil groups are often worked on collectively, and because the correlation between the groups is reasonably well known in most intervals. This zonation holds great promise for improving the chronostratigraphic framework and biostratigraphic correlations needed in paleoenvironmental and paleoceanographic investigations.

INTRODUCTION

Planktonic foraminifers, nannofossils, and calpionellids are the primary fossil groups used in the biostratigraphy of Mesozoic calcareous deep-sea sediments. Cenozoic zonation schemes of the former two groups possess sufficient resolution for most detailed applications (e.g., Moore and Romine, 1981; Berggren and others, 1985, this volume). Mesozoic microfossil zonations, on the other hand, offer diminished resolution and thus biostratigraphy becomes a weak link in many geological studies.

Original zonations for Cretaceous planktonic foraminifers, calcareous nannofossils and calpionellids were largely developed in Tethyan and other low-latitude sections over 20 years ago (e.g., Bolli, 1957, 1959, 1966; Moullade, 1966; Pessagno, 1967; Sigal, 1967, 1977; Allemann and others, 1971; Thierstein, 1971, 1973; Van Hinte, 1972, 1976; Longoria, 1974; Sissingh, 1977). These zonations were modified in part by the addition of subzones (e.g., Manivit and others, 1977); however, the resolution for all groups remains low at an average of 2–6 my/zone and 1–3 my/subzone. At the same time, there have been advances in techniques and taxonomy. For planktonic foraminifers and nannofossils, processing techniques have evolved allowing the study of indurated sedimentary rocks such as limestones (e.g., Postuma, 1971; Premoli Silva, 1977; Monechi and Thierstein, 1985; Sliter, 1989; Premoli Silva and Sliter, unpubl. data) which had previously only been datable using calpionellids within the Tithonian (Upper Jurassic) to Valanginian strata. These new techniques have led to the study of numerous additional land sections (e.g., Erba and Quadrio, 1987; Tornaghi and others, 1989). Taxonomic advances which include the clarification of existing and the discovery of new taxa, also have lead to increased potential resolution as there are more species available for biostratigraphy.

The Deep Sea Drilling Project and Ocean Drilling Program have recovered many new Cretaceous sections in the last twenty years. These include sequences from high latitudes and from all of the major ocean basins. Many of these sections are more complete than those in which original zonations were developed. Therefore, through the addition of zones and subzones, new zonal schemes (e.g., Bralower and others, 1993) offer higher resolution than those previously proposed. Several biostratigraphic schemes (e.g., Bralower and others, 1989) have proposed a series of non-zonal biohorizons. These are events which are, largely for preservational and biogeographic reasons, undefinable in a majority of sequences, but they offer the ability to obtain higher resolution than traditional zonations. However, because of the limited number of sections in which they can be currently defined, the relative order of subsidiary biohorizons is still not well established in most Cretaceous intervals. Since the correlation between different microfossil biostratigraphies is becoming better established in most intervals, higher biostratigraphic resolution with maximum precision is best obtained by integrating different schemes.

In this paper, we propose an informal integrated Cretaceous calcareous nannofossil, calpionellid and planktonic foraminifer biostratigraphic scheme consisting of 73 zones. This zonation is informal as we have not formally defined each unit according to the criteria recommended by the International Subcommission on Stratigraphic Classification (Hedberg, 1976). Advantages of integration include: (1) ability to refine the stratigraphy of sequences with poor preservation by combining events based on the most resistant taxa of two microfossil groups; (2) correlation of biostratigraphies where one fossil group is better preserved than the other as is often the case in Cretaceous sections (e.g., Tarduno and others, 1992); (3) checking results of one fossil group with the other permitting increased biostratigraphic precision; and (4) planktonic foraminifers generally provide higher biostratigraphic resolution in certain intervals (e.g., Aptian, lower to mid Cenomanian) than calcareous nannofossils, while the opposite is true for the Barremian, Albian and upper Cenomanian to lower Turonian. In this zonation, we utilize calcareous nannofossils which range throughout the Cretaceous Period; calpionellids, which range from the Tithonian (uppermost Jurassic) to the middle part of the Valanginian; and planktonic foraminifers, which originate in the Jurassic, but do not become biostratigraphically useful until the Barremian. Be-

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cause the ranges of calpionellids and planktonic foraminifers do not overlap, the integrated scheme is only based on two microfossil groups in any one interval.

CRETACEOUS MICROFOSSIL BIOSTRATIGRAPHY

This investigation is based upon compilation of previous planktonic foraminifer and calcareous nannofossil biostratigraphies as well as selective reinvestigation of parts of particular sections. Range charts for these reinvestigated sections are published elsewhere (Bralower and others, 1994). Correlations between calcareous nannofossils and calpionellids are taken entirely from the literature. In this section, we briefly discuss the current Cretaceous zonations of the three microfossil groups and the correlations between them, followed by the procedure with which the integrated zonation is constructed.

Calcareous Nannofossil Zonation

Cretaceous calcareous nannofossil zonations have developed over the last twenty years, yet the early schemes of Thierstein (1971, 1973; both Lower Cretaceous), Sissingh (1977) and Roth (1978; both cover the entire Cretaceous) are still widely applied. A comprehensive summary of these zonations is given in Perch-Nielsen (1985). High latitude zonal schemes have been proposed by Wise and Wind (1977) and Wise (1983; Aptian through Maastrichtian) and Watkins (1992; Coniacian through Maastrichtian). These schemes as well as those of Manivit and others (1977; Aptian through Coniacian) and Applegate and Bergen (1988; Valanginian through Cenomanian) have included subzonal units in order to improve biostratigraphic resolution. Detailed evaluation of zonations, including the choice of markers, and the availability of alternative events is given in Bralower and others (1989) for the Berriasian and Valanginian stages; Bralower (1987), Channell and others (1987) and Erba and Quadrio (1987) for the Valanginian through Aptian; Erba (1988) for the Aptian and Albian; Bralower and others (1993) for the Aptian and Albian, Bralower and others (1994) for the upper Barremian to lower Aptian, Bralower (1988) for the Cenomanian/Turonian boundary interval; Bralower and Siesser (1992) for the Aptian through Maastrichtian; and Mutterlose (1992) for the entire Early Cretaceous Period. Several of these studies have proposed alternative zonations for particular intervals. For example, Bralower and others (1989) proposed a series of new subzones for the Berriasian and lower Valanginian stage; Bralower (1987) defined several subzones in the upper Hauterivian and Barremian intervals; Erba (1988) defined a series of new zones for the Aptian and Albian intervals; Bralower and others (1993) proposed several informal subzones for the Aptian and Albian intervals which were tied to the zonation of Roth (1978); and Bralower (1988) defined new zones and subzones in the Cenomanian/Turonian boundary interval.

Several of these studies also led to the addition of non-zonal nannofossil events or biohorizons to biostratigraphic schemes (e.g., Bralower and others, 1989; Bralower and others, 1993). These events can usually be determined in expanded DSDP/ODP sites with suitable preservation but are more difficult to detect in land sequences. Because of the limited number of sequences in which these events have currently been established, their relative order is still not entirely certain. Recovery of more suitable sequences in the future should allow these events to become more standard components of nannofossil biostratigraphies.

Even though certain schemes can be widely applied in particular time intervals, there is no zonal scheme which is globally applicable. This situation is especially apparent in high latitude sequences. The geographic range over which zonations are applicable depends on relative temperature gradients in the oceans (e.g., Mutterlose, 1989). These gradients changed throughout the Cretaceous Period the result being that at certain times cosmopolitan schemes are widely applicable, but at others, the correlation between high and low latitude schemes is still uncertain. For Lower Cretaceous strata, well defined zonations for Boreal sections exposed in Northern Europe (e.g., Crux, 1989) are still poorly correlated to low latitude zonal schemes due to the absence of common marker taxa. Aptian and Albian high- and low-latitude zonal schemes have been correlated based on the co-occurrence of markers at temperate ODP Site 763 on the Exmouth Plateau, Indian Ocean (Bralower, 1992). Similarly, Watkins (1992) showed that cosmopolitan schemes were applicable from the Coniacian to the lower Campanian on the Kerguelen Plateau (Indian Ocean), but that Maastrichtian schemes were not.

In general, Lower Cretaceous zonations for low latitude and temperate areas are rather uniform, but Upper Cretaceous zonations are not. The two most commonly applied schemes, those of Sissingh (1977) and Roth (1978), have a limited number of common events in Upper Cretaceous units and neither is entirely satisfactory for this interval. This has been clearly demonstrated in ODP Sites 762 and 763 on the Exmouth Plateau (Bralower and Siesser, 1992).

Correlations between nannofossil zones, biohorizons, and stage boundaries are moderately well determined for Lower Cretaceous units where stratotype and parastratotype sequences are, for the most part, apparently complete and fossiliferous. More uncertainties exist in Upper Cretaceous units where some boundaries are poorly exposed, sparsely fossiliferous, and apparently incomplete (e.g., Burnett and others, 1992). Correlation between Upper Cretaceous nannofossil zones and stage boundaries, shown in Figure 1, may, therefore, undergo future revision.

The calcareous nannofossil scheme utilized here is that of Roth (1978; Fig. 1). This scheme has been selected because: (1) a scheme is needed to cover the entire Cretaceous Period, and (2) the correlation between nannofossil and planktonic foraminiferal biostratigraphies is largely based on results from DSDP/ODP sequences on which the Roth (1978) scheme was also constructed. The Sissingh (1977) scheme was based on results from land sequences (largely in Europe) where planktonic foraminiferal data are often unavailable or where the markers used here are unreported.

In order to improve resolution in Upper Cretaceous intervals where there are few widely applicable, reliable microfossil events, we have proposed four new informal subzonal divisions of Roth's (1978) zones (Fig. 1). Campanian zone NC19 is divided into two subzones, NC19A (from the base of *Ceratolithoides aculeus* to the base of *Tetralithus gothicus*) and NC19B (from the base of *T. gothicus* to the base of *T. trifidus*). Maastrichtian Zone NC21 (from the top of *T. trifidus* to the base of *Lithraphidites quadratus*) is divided into two subzones, NC21A and NC21B, by the last occurrence of *Reinhardtites levis*. The

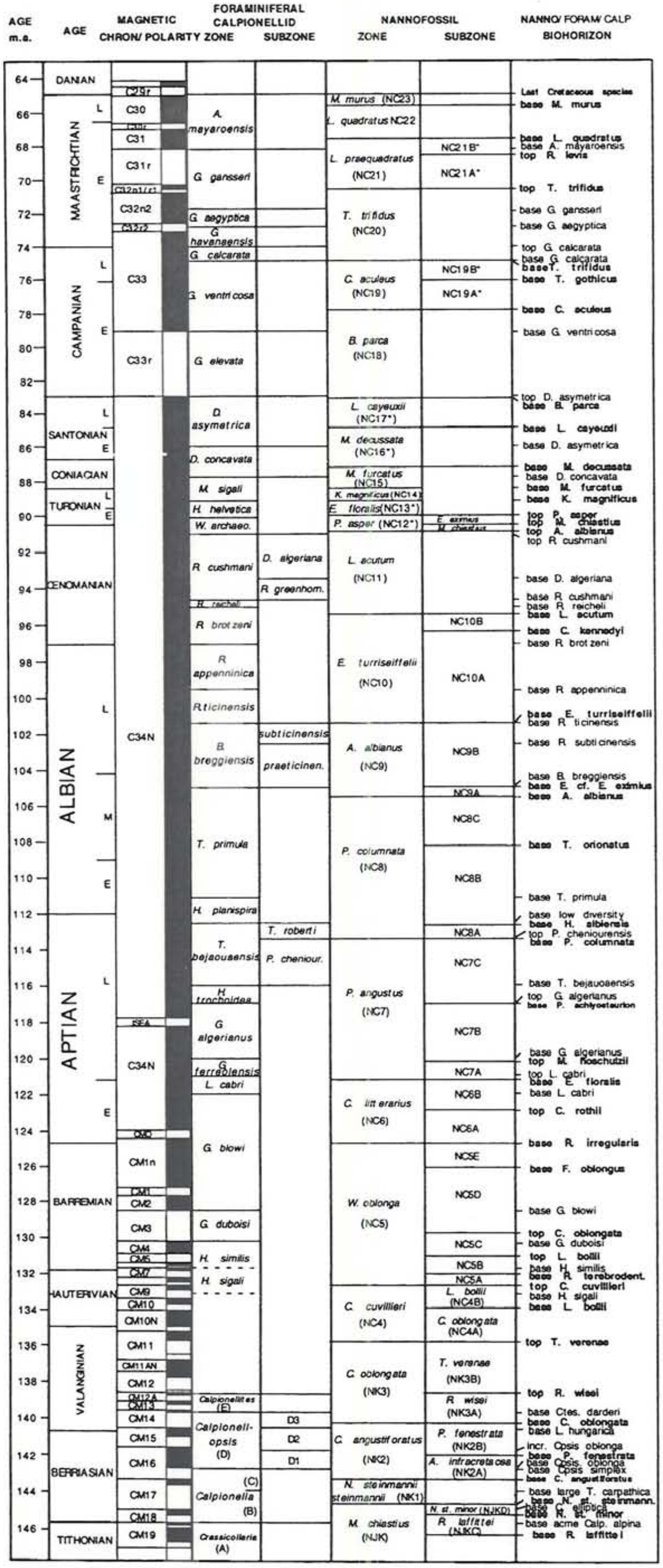

Fig. 1.—Integrated Cretaceous biochronology and magnetochronology. Chronostratigraphy and geomagnetic polarity timescales are after Harland and others (1989). Tithonian through Valanginian calpionellid zones/subzones and Hauterivian through Maastrichtian planktonic foraminiferal zones/subzones are shown in the same column. New nannofossil subzones are shown with asterices. Zonal markers are shown on the right. Nannofossil events are in bold type; planktonic foraminiferal/calpionellid events are in light type. See text for details on zonation schemes and correlations between biostratigraphies and the geomagnetic polarity timescale.

markers for these subzones are solution resistant and observed over a broad geographic area.

Calpionellid Zonation

The calpionellid biostratigraphy utilized here is the standard zonation of Allemann and others (1971) which has been widely applied in sequences across the Tethyan Realm from southern Europe to Mexico. This scheme (Fig. 1) has been augmented by the addition of several subzones (e.g., Remane, 1971). Problems related to the statistical basis of several events in these zonations, which are not based on first occurrences but on changes in relative abundances, have been discussed by Remane (1985) and Channell and Grandesso (1987). This calpionellid zonation has been accurately correlated with ammonite zonations (e.g., Allemann and Remane, 1979) and with stratotype stage boundaries.

Planktonic Foraminiferal Zonation

Cretaceous planktonic foraminiferal biostratigraphy has developed over several decades (e.g., Bolli, 1966; Moullade, 1966; Barr, 1972; Premoli Silva and Bolli, 1973; Longoria, 1974, 1984; Moullade, 1974; van Hinte, 1976; Masters, 1977; Sigal, 1977; Robaszynski, Caron and others, 1979, 1984; Wonders, 1980; Leckie, 1984; Caron, 1985; Sliter, 1989; Huber, 1992). A wide variety of different zonal schemes is still utilized. Evolution of the different schemes showing their correlation is illustrated in Figure 2. Three major problems exist in the application of planktonic foraminiferal zonation: (1) the correlation between high- and low-latitude zonations is not well established (e.g., Huber, 1992), (2) a number of events (e.g., the first occurrence of *Abathomphalus mayaroensis*) have been shown to be distinctly diachronous, and (3) the biostratigraphy of the Hauterivian through Aptian interval of earliest evolution of planktonic foraminifers is in a state of flux.

The planktonic foraminiferal biostratigraphic scheme utilized here (Fig. 1) is that of Sliter (1989, 1992) which is based largely on the summary of Caron (1985). The Caron (1985) scheme is a compilation of zonations for various intervals of the Cretaceous Period. This scheme can be applied to washed residues as well as to thin sections of indurated sediments (e.g., Sliter and Leckie, 1993). The Barremian and lower Aptian intervals are in a state of flux and need a re-examination of the tiny, early species of planktonic foraminifera, particularly of the genus *Globigerinelloides*, from deep sea and land sections (see below). With the exception of the Hauterivian/Barremian boundary, which is likely to undergo future revision, the status of correlation between planktonic foraminifer zones and stage boundaries (Fig. 1) is similar to that of the calcareous nannofossils. Uncertainties exist for particular Upper Cretaceous boundaries through lack of suitable exposure, presence of condensed horizons, and absence of zonal marker taxa. For example, no foraminiferal events lie close to the Santonian/Campanian boundary, and the upper and lower limits of the Coniacian are hard to detect using planktonic foraminifera.

Problems with the Barremian-Lower Aptian Interval

The first occurrence (FO) of the genus *Globigerinelloides* (*G. duboisi, G. gottisi, G. blowi*) has previously been used as an important biostratigraphic datum within basal Aptian strata (Moullade, 1966; Van Hinte, 1976; Sigal, 1977; Caron, 1985). However, more recent work has shown that various "species" of *Globigerinelloides* occur within Barremian strata (e.g., Sigal, 1979; Moullade and others, 1988; Leckie and Bralower, 1991; Coccioni and others, 1992). The most reliable datum for the Barremian/Aptian boundary is the FO of the calcareous nannofossil *Rucinolithus irregularis* (Thierstein, 1973; Bralower, 1987; Coccioni and others, 1992; Bralower and others, 1993). Chron M0, the uppermost magnetic anomaly in the Early Cretaceous M-sequence, occurs just above the boundary (Channell and others, 1979; Tarduno and others, 1989; Channell and Erba, 1992; Coccioni and others, 1992). A revised but preliminary planktonic foraminiferal zonal scheme for the lower Barremian through lower Aptian is needed in view of the recent and ongoing work on this interval.

Two different zonal schemes have emerged. Coccioni and others (1992), in a study of limestone thin sections from the Umbrian Apennines of central Italy (Gorgo a Cerbara), have documented the FO of *G. duboisi* within the *Micrantholithus hoschulzii* nannofossil Zone, just below polarity zone Chron M1. This correlates with the uppermost ammonite zone of the lower Barremian in southern Spain. The FO of *G. blowi* is in the upper part of the *M. hoschulzii* Zone (upper Barremian) between Chrons M1 and M0. The FO of *Hedbergella similis* predates both of these *Globigerinelloides* datums according to Coccioni and others (1992). Their lower Barremian-lower Aptian planktonic foraminiferal biostratigraphy is as follows: lower Barremian *H. similis* Zone, mid-Barremian *G. duboisi* Zone, upper Barremian-lower Aptian *G. blowi* Zone, and lower Aptian *Leupoldina cabri* Zone.

In a study of well preserved specimens from ODP Site 641 in the eastern North Atlantic and a reassessment of planktonic foraminiferal distributions in nearby DSDP Site 398 (Sigal, 1979), Leckie has established a different zonal scheme for the mid-Barremian-lower Aptian interval (Leckie and Bralower, 1991; Bralower and others, 1994; Leckie, unpubl. data). Following Moullade (1966; *Hastigerina* aff. *H. simplex* Zone) and Sigal (1977), the *"Clavihedbergella" eocretacea* Zone represents a total range zone in the upper lower or mid-Barremian interval (*Watznaueria oblonga* nannofossil Zone; Bralower and others, 1994). The FO of *Globigerinelloides* aff. *G. duboisi-gottisi* group is in the lower part of the *"C." eocretacea* Zone. The FO of large, well-developed *Hedbergella similis* s.s. and the FO of *G.* aff. *G. blowi* are near the last occurrence (LO) of *"C." eocretacea* in the upper Barremian interval of Site 641. A similar sequence of datums was recorded by Sigal (1979) in nearby Site 398. The FO of *H. similis* above the FO of the *G.* aff. *G. duboisi-gottisi* group is at apparent odds with the findings of Coccioni and others (1992). The LO of *H. similis* at Site 641 is just above Chron M0, but other studies have shown this taxon to range into the mid-Aptian (e.g., Longoria, 1974; Sigal, 1977, 1979; Sliter, 1992). The discrepancy in the stratigraphic range data for *H. similis* may result from taxonomic differences between workers, particularly in the differentiation of ancestral and descendant forms (Leckie, unpubl. data). Given the present taxonomic and stratigraphic uncertainties, not only in *H. similis* but also in the tiny early species of *Globigerinelloides*, the following alternate informal zonal scheme is proposed for the lower Barremian through lower Aptian interval: lower and mid-

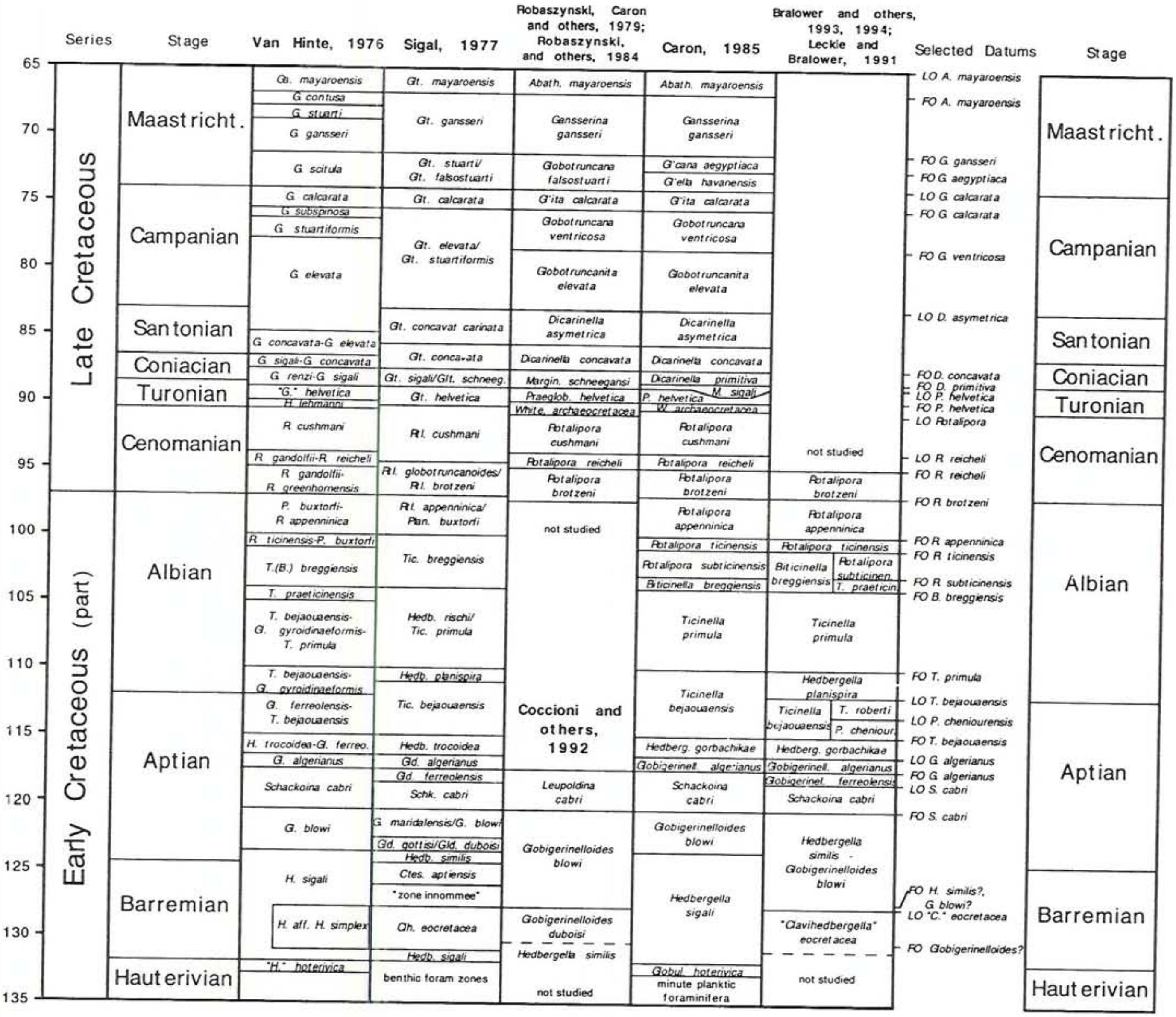

Fig. 2.—Evolution of planktonic foraminiferal zonations. Datums used to define the zonal units used here are shown at right.

Barremian *"C." eocretacea* Zone (total range zone), upper Barremian and lower Aptian *H. similis-G. blowi* Zone, and lower Aptian *Schackoina cabri* Zone (Fig. 2).

CORRELATION BETWEEN MICROFOSSIL BIOSTRATIGRAPHIES

Detailed correlation between calcareous nannofossils and planktonic foraminiferal zonations can best be achieved in expanded sections with good microfossil preservation. Such sections are mainly found in the deep sea. Land sections contain poorer microfossil preservation, especially of calcareous nannofossils, and numerous condensed intervals. Exceptions to this are the sections in the *Fosse Vocontienne* (Moullade, 1966; Thierstein, 1973) and some Upper Cretaceous intervals in the Western Interior Basin (e.g., Leckie, 1985; Bralower 1988) which contain moderate microfossil preservation, are relatively expanded, and provide critical macrofossil biostratigraphic, and thus chronostratigraphic, correlations. In addition, detailed studies of Cretaceous sections in the Umbrian Apennines of Italy (e.g., Premoli Silva, 1977; Monechi and Thierstein, 1985; Coccioni and others, 1992; Premoli Silva and Sliter, unpubl. data) provide important information. Our correlation between nannofossil and planktonic foraminiferal biostratigraphies is obtained from the *Fosse Vocontienne* sections studied by Moullade (1966) and Thierstein (1973), from the Piobbico Core drilled in the Umbrian Apennines of Italy investigated by Erba (1988) and Tornaghi and others (1989), from DSDP and ODP sites in the Atlantic (Sites 545 and 547 in the Moroccan basin and Site 641 on the Galicia Margin; Leckie, 1984; Wiegand, 1984; Bralower, 1992; Bralower and others, 1993; Bralower and others, 1994) and Pacific (Site 167 on the Magellan Rise and Site 463 in the Mid Pacific Mountains; Tarduno and others,

LOCATION	MACROFOSSIL ZONE	STAGE	40Ar/39Ar AGE (Ma)	NANNOFOSSIL MARKERS	ZONE R78	ZONE S77	STAGE
Montrose, CO Mancos Shale (O&C, Loc. 5)	*E. jenneyi*	U. Camp.	74.76±0.45	*A. cymbiformis* *B. parca* *E. eximius* *R. anthophorus*	NC20	CC22	Top Camp.
Cedar Creek, SD Pierre Shale (O&C, Loc. 7)	*D. nebrascense*	U. Camp.	75.89±0.72	*A. cymbiformis* *B. parca* *E. eximius* *R. anthophorus*	NC20	CC22	Top Camp.
Winnett, MT Telegr. Ck. Fm. (O&C, Loc. 11)	*D. bassleri*	Top Sant.	83.83±0.43	*P. regularis* *L. grillii* *R. anthophorus* *M. staurophora* *B. "preparca"* No *B. parca s.s.*	NC17	CC17	Top Sant.
Marias River, MT Colorado Shale (O&C, Loc. 13)	*S. preventric.*	m. Con.	88.34±0.60	*E. floralis* *M. furcatus* *M. staurophora* *R. anthophorus*	NC15	CC14-CC15	U. Con-L. Sant
Cone Hill, MT Marias River Sh. (O&C, Loc. 14)	*N. judii*	Top Cen.	93.55±0.47	*E. eximius* *Q. gartneri* No *A. albianus* No *M. chiastius* No *L. maleformis*	NC12	CC11	L. Tur.
Carbon County, WY (O&C, Loc. 15)	*D. pondi*	U. Cen.	94.63±0.61	*A. albianus* *C. kennedyi* *M. chiastius* *G. segmentatum* *V. octoradiata*	NC11-NC12	CC10	U. Cen.
Niobrara, WY Greenhorn Lst. (O&C, Loc. 16)	*A. amphibolum*	m. Cen.	94.93±0.53	*A. albianus* *L. acutum* *C. kennedyi* No *G. segmentatum* No *V. octoradiata*	NC11	CC9	m. Cen.

O&C---Obradovich and Cobban (1975), zonal, stage designations and Ar/Ar ages from Obradovich (1993). R78-Roth (1978); S77-Sissingh (1977)

FIG. 2.—Continued.

1989), and from numerous sections in the Western Interior Basin of North America (Leckie, 1985; Bralower, 1988) and Northern Europe (Hart and Bigg, 1981; Bralower, 1988; Jarvis and others, 1988). Correlation between Upper Cretaceous zonations are based on the Gubbio sections (Premoli Silva, 1977; Monechi and Thierstein, 1985; Premoli Silva and Sliter, unpubl. data) and DSDP sites in the South Atlantic Ocean (Poore and others, 1983; Boersma, 1984; Manivit, 1984).

Numerous other deep-sea sections which serve as a basis for our high-resolution, calcareous nannofossil biostratigraphy are in the process of detailed planktonic foraminifer biostratigraphic investigation. These include: North Atlantic DSDP Site 398 and ODP Site 641 and Indian Ocean ODP Sites 761, 762 and 763. South Atlantic DSDP Site 511 has a detailed planktonic foraminifer biostratigraphy (Krashenninikov and Basov, 1983) but lacks traditional marker taxa which are useful in the other sections. Somewhat different correlations between calcareous nannofossil and planktonic foraminiferal zonations exist in high-latitude sections (e.g., Huber and Watkins, 1992) where different zonal markers have proven to be useful (e.g., Huber, 1992; Watkins and others, 1992).

Correlation between calcareous nannofossil and calpionellid biostratigraphy is based on various sequences in the *Fosse Vocontienne* (e.g., Le Hēgarat and Remane, 1968; Thierstein, 1973; Thierstein, 1975; Bralower and others, 1989), the Umbrian Apennines (e.g., Cirilli and others, 1984; Lowrie and

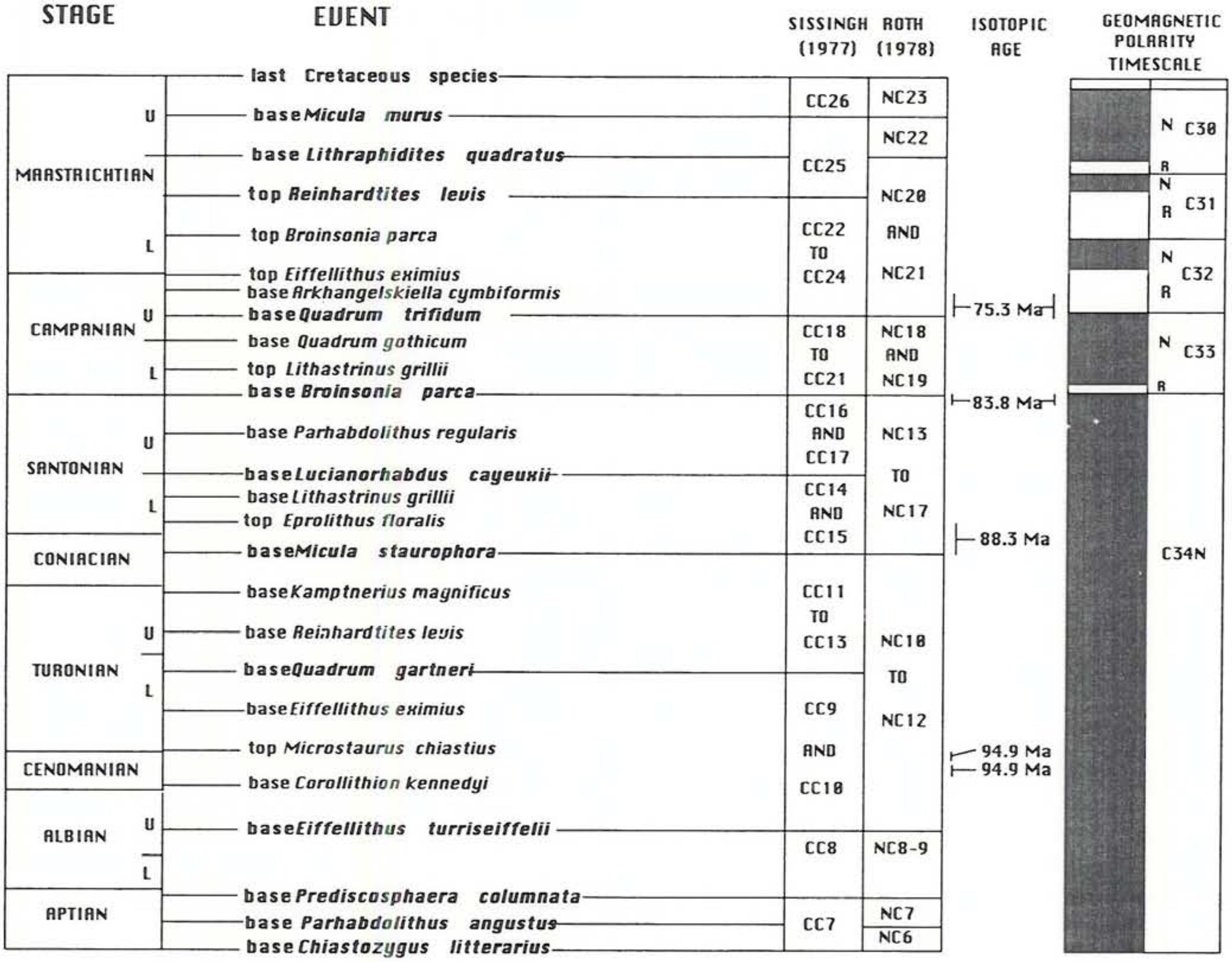

FIG. 3.—Correlation of calcareous nannofossil zonations of Sissingh (1977) and Roth (1978) and non-zonal biohorizons with the geomagnetic polarity timescale. Only those zones relevant to the discussion are divided. The correlation shown is the scheme discussed in detail by Bralower and Siesser (1992). This correlation allows indirect ties between Western Interior bentonite isotopic ages and the geomagnetic polarity timescale (see text for complete discussion).

Channell, 1984; Bralower and others, 1989), and Southern Alps (Ogg, 1981; Channell and Grandesso, 1987; Channell and others, 1987) of Italy and DSDP Site 534 in the western North Atlantic (Roth, 1983; Remane, 1983; Bralower and others, 1989). The numerous sequences in which these correlations have been established indicate few problems with the ties shown (Fig. 1).

BIOMAGNETOSTRATIGRAPHIC CORRELATION

Microfossil biostratigraphic correlation with the geomagnetic polarity timescale has been the subject of intense recent investigation. Correlation of M-sequence chrons with nannofossils and calpionellids is based on studies of sequences in the Umbrian Apennines (Lowrie and others, 1980; Lowrie and Alvarez, 1984; Cirilli and others, 1984; Bralower, 1987; Bralower and others, 1989) and Southern Alps (Channell and others, 1979; Ogg, 1981; Bralower, 1987; Channell and Grandesso, 1987; Channell and others, 1987; Bralower and others, 1989; Channell and Erba, 1992) of Italy, DSDP Site 534 in the western North Atlantic (Wind, 1978; Roth, 1978; Ogg, 1983; Roth, 1983; Bralower and others, 1989) and Pacific DSDP Sites 167 and 463 (Tarduno and others, 1989). Planktonic foraminifer zones have been correlated to the upper part of the M-sequence only in one section, at Gorgo a Cerbara in the Umbrian Apennines (Coccioni and others, 1992; Premoli Silva, pers. commun., 1992). Correlation of stage boundaries and the geomagnetic polarity timescale has been discussed in most of these previously cited references. We have modified the correlation of the Hauterivian/Barremian boundary to Chron CM4 as reported by Cecca and others (1994) based on ammonite biostratigraphy of the Gorgo a Cerbara section. Reversed magnetic polarity zones within the long normal polarity interval (C34N) have been reported by Vandenberg and others (1978), Tarduno (1990) and Tarduno and others (1992). High-frequency reversals in the middle Albian interval (Tarduno and others, 1992) have only been reported from one sequence and are not included in our chronology although the biostratigraphic correlation of the late Aptian ISEA reversal is well established (Tarduno, 1990; Fig. 1). Correlation between Upper Cretaceous magnetic

TABLE 1.—INTEGRATED ZONES

ZONE	BASE	TOP
IC73	base ***Micula murus***	Last **Cretaceous species**
IC72	base ***Lithraphidites quadratus***	base ***Micula murus***
IC71	base *Abathomphalus mayaroensis*	base ***Lithraphidites quadratus***
IC70	top ***Reinhardtites levis***	base *Abathomphalus mayaroensis*
IC69	top ***Tetralithus trifidus***	top ***Reinhardtites levis***
IC68	base *Gansserina gansseri*	top ***Tetralithus trifidus***
IC67	base *Globotruncana aegyptica*	base *Gansserina gansseri*
IC66	top *Globotruncanita calcarata*	base *Globotruncana aegyptica*
IC65	base *Globotruncanita calcarata*	top *Globotruncanita calcarata*
IC64	base ***Tetralithus gothicus***	base *Globotruncanita calcarata*
IC63	base ***Ceratolithus aculeus***	base ***Tetralithus gothicus***
IC62	base *Globotruncana ventricosa*	base ***Ceratolithus aculeus***
IC61	top ***Lithraphidites grillii***	base *Globotruncana ventricosa*
IC60	base ***Broinsonia parca***	top ***Lithraphidites grillii***
IC59	base ***Lucianorhabdus cayeuxii***	base ***Broinsonia parca***
IC58	base *Dicarinella asymetrica*	base ***Lucianorhabdus cayeuxii***
IC57	base ***Micula decussata***	base *Dicarinella asymetrica*
IC56	base *Dicarinella concavata*	base ***Micula decussata***
IC55	base ***Marthasterites furcatus***	base *Dicarinella concavata*
IC54	base ***Kamptnerius magnificus***	base ***Marthasterites furcatus***
IC53	top ***Parhabdolithus asper***	base ***Kamptnerius magnificus***
IC52	top ***Microstaurus chiastius***	top ***Parhabdolithus asper***
IC51	top ***Axopodorhabdus albianus***	top ***Microstaurus chiastius***
IC50	top *Rotalipora cushmani*	top ***Axopodorhabdus albianus***
IC49	top ***Corollithion kennedyi***	top *Rotalipora cushmani*
IC48	base ***Vagalapilla octoradiata***	top ***Corollithion kennedyi***
IC47	base *Dicarinella algeriana*	base ***Vagalapilla octoradiata***
IC46	base *Rotalipora cushmani*	base *Dicarinella algeriana*
IC45	base *Rotalipora reicheli*	base *Rotalipora cushmani*
IC44	base ***Lithraphidites acutum***	base *Rotalipora reicheli*
IC43	base ***Corollithion kennedyi***	base ***Lithraphidites acutum***
IC42	base *Rotalipora brotzeni*	base ***Corollithion kennedyi***
IC41	base ***Gartnerago nanum***	base *Rotalipora brotzeni*
IC40	base *Rotalipora appenninica*	base ***Gartnerago nanum***
IC39	base ***Eiffellithus turriseiffelii***	base *Rotalipora appenninica*
IC38	base *Rotalipora subticinensis*	base ***Eiffellithus turriseiffelii***
IC37	base *Biticinella breggiensis*	base *Rotalipora subticinensis*
IC36	base ***Axopodorhabdus albianus***	base *Biticinella breggiensis*
IC35	base ***Tranolithus orionatus***	base ***Axopodorhabdus albianus***
IC34	base ***Corollithion signum***	base ***Tranolithus orionatus***
IC33	base *Ticinella primula*	base ***Corollithion signum***
IC32	base low diversity forams	base *Ticinella primula*
IC31	base ***Hayesites albiensis***	base low diversity forams
IC30	base ***Prediscosphaera columnata***	base ***Hayesites albiensis***
IC29	base *Ticinella bejaouaensis*	base ***Prediscosphaera columnata***
IC28	top *Globigerinelloides algerianus*	base *Ticinella bejaouaensis*
IC27	base *Globigerinelloides algerianus*	top *Globigerinelloides algerianus*
IC26	top *Leupoldina cabri*	base *Globigerinelloides algerianus*
IC25	base ***Eprolithus floralis***	top *Leupoldina cabri*
IC24	base *Leupoldina cabri*	base ***Eprolithus floralis***
IC23	top ***Conusphaera rothii***	base *Leupoldina cabri*
IC22	base ***Rucinolithus irregularis***	top ***Conusphaera rothii***
IC21	base ***Flabellites oblongus***	base ***Rucinolithus irregularis***
IC20	base *G. blowi, H. similis*	base ***Flabellites oblongus***
IC19	top ***Calcicalathina oblongata***	base *G. blowi, H. similis*
IC18	base *Globigerinelloides?*	top ***Calcicalathina oblongata***
IC17	top ***Lithraphidites bollii***	base *Globigerinelloides?*
IC16	base ***Rucinolithus terebrodentarius***	top ***Lithraphidites bollii***
IC15	top ***Cruciellipsis cuvillieri***	base ***Rucinolithus terebrodentarius***
IC14	base ***Lithraphidites bollii***	top ***Cruciellipsis cuvillieri***
IC13	top ***Tubodiscus verenae***	base ***Lithraphidites bollii***
IC12	top ***Rucinolithus wisei***	top ***Tubodiscus verenae***
IC11	base Calpionellites darderi	top ***Rucinolithus wisei***
IC10	base ***Calcicalathina oblongata***	base Calpionellites darderi
IC9	base Lorenziella hungarica	base ***Calcicalathina oblongata***
IC8	incr Calpionellopsis oblonga	base Lorenziella hungarica
IC7	base ***Percivalia fenestrata***	incr Calpionellopsis oblonga
IC6	base Calpionellopsis simplex	base ***Percivalia fenestrata***
IC5	base ***Cretarhabdus angustiforatus***	base Calpionellopsis simplex
IC4	base large Tintinnopsella carpathica	base ***Cretarhabdus angustiforatus***
IC3	base ***Nannoconus st. steinmannii***	base large Tintinnopsella carpathica
IC2	base ***Nannoconus st. minor***	base ***Nannoconus st. steinmannii***
IC1	base acme Calpionella alpina	base ***Nannoconus st. minor***

Taxa in bold: calcareous nannofossils, light type: planktonic foraminifers, underlined: calpionellids.

chrons and calcareous nannofossil and planktonic foraminiferal zones is based on investigations of the Gubbio sequences (Alvarez and others, 1977; Monechi and Thierstein, 1985; Premoli Silva and Sliter, unpubl. data), sections in the South Atlantic (Poore and others, 1983; Tauxe and others, 1983; Boersma, 1984; Manivit, 1984; Chave, 1984; Stradner and Steinmetz, 1984; Huber, 1991), Southern Ocean (Huber, 1990; Pospichal and Wise, 1990); Pacific (Monechi and others, 1985) and the eastern Indian Ocean (Galbrun, 1992; Bralower and Siesser, 1992). Minor modifications of the current scheme (Fig. 1) are to be expected in the future as new, expanded sequences with suitable microfossil preservation are recovered. Once again, the correlations illustrated are most consistent for low- and mid-latitude sections. Paleobiogeographic factors causing the diachroneity of particular planktonic foraminiferal and nannofossil events with respect to magnetostratigraphy at high-latitude sites are discussed by Huber and Watkins (1992).

DIRECT CALIBRATION OF RADIOMETRIC AGES AND NANNOFOSSIL BIOSTRATIGRAPHY

Inherent in the construction of any time scale is the correlation between biostratigraphy and isotopic ages measured on a variety of different igneous and sedimentary materials. Cretaceous time scales differ significantly according to their selectivity of radiometric data. Some studies, for example, Kent and Gradstein (1985) and Obradovich (1993) use only those isotopic dates with the lowest geochemical uncertainties and exclusively volcanic and pyroclastic horizons. Others, such as Harland and others (1989) and Gradstein and others (1993), utilize isotopic data less selectively and apply statistical techniques to arrive at the "best" age estimate for individual boundaries. No matter which approach is chosen, however, the precision of time scales depends partly on the precision with which an isotopic age is correlated with biostratigraphic elements.

Early Cretaceous Ages

Two recently published Early Cretaceous isotopic ages have precise biostratigraphic ties. Zircon fractions from closely spaced bentonites in the middle Berriasian of the Great Valley Group, northern California have been dated at 137 +1.6/-0.6 Ma using U/Pb. These horizons have been correlated to the *Cretarhabdus angustiforatus* (NK-2) nannofossil Zone, *Assipetra infracretacea* Subzone (Bralower and others, 1990) and indirectly to magnetic chrons CM16 and CM16n. Basalt samples recovered from the Ontong Java Plateau at ODP Site 807 have been dated using $^{40}Ar/^{39}Ar$ providing a mean of 122 Ma (Mahoney and others, 1993). Directly-overlying sediments lie in the lower Aptian *Chiastozygus litterarius* (NK-6) nannofossil Zone (E. Erba, pers. commun., 1993) and *G. blowi* foraminifer Zone (Sliter and Leckie, 1993). The normal magnetic polarity of this basement indicates that it correlates to the base of the Cretaceous long normal polarity interval (Tarduno and others, 1991).

Late Cretaceous Ages

Common elements of all Cretaceous time scales have been the K/Ar ages of sanidines and biotites from Upper Cretaceous bentonites deposited in macrofossiliferous sections of the Western Interior Basin (Obradovich and Cobban, 1975). These bentonite ages have been correlated with macrofossil zones, mainly those of ammonites, allowing indirect ties to European stage stratotype and parastratotype sequences. Recently, Obradovich (1993) remeasured many of these same units, as well as newly collected layers, with the extremely precise $^{40}Ar/^{39}Ar$ radiometric system. These dates have led to a precise Upper Cretaceous time scale with tie points to stages at over 30 different levels. This part of the Cretaceous time scale is now well established and should change very little in the future.

One possible problem with the established Upper Cretaceous time scale is that several of the correlations between Western

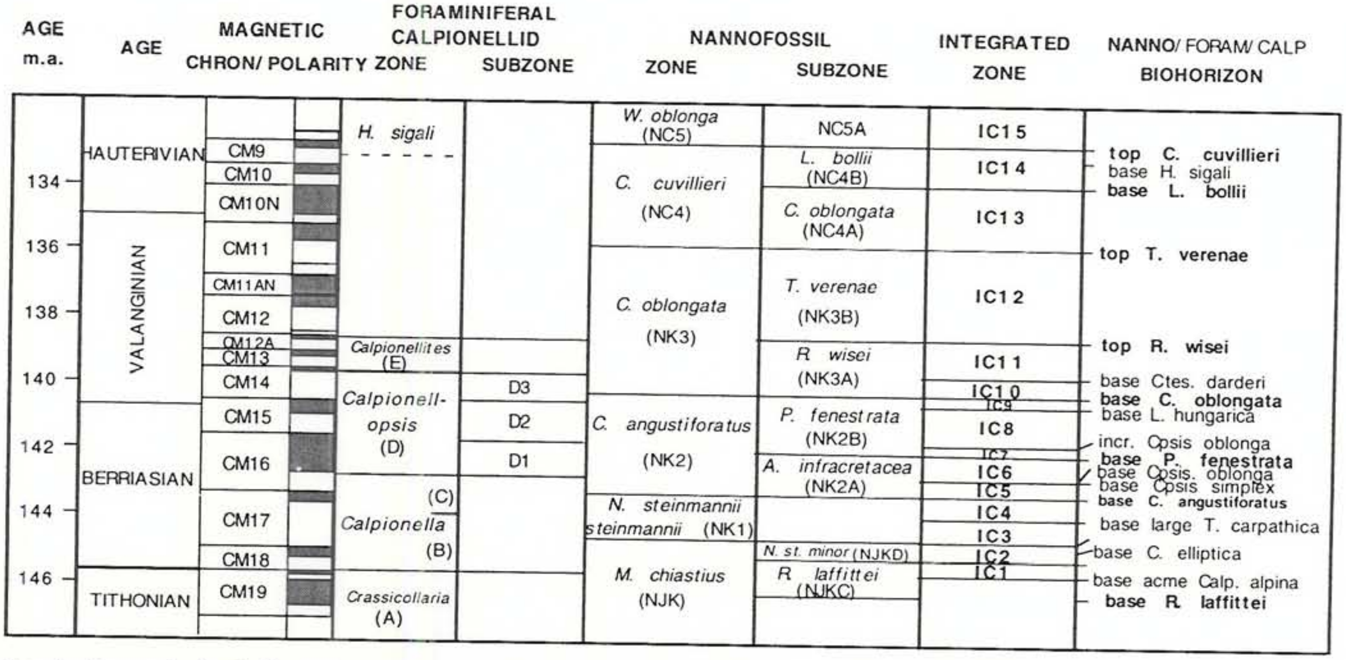

FIG. 4.—Integrated microfossil zonation for the Berriasian and Valanginian interval. Zonal markers are shown on the right. Nannofossil events are in bold type; planktonic foraminiferal/calpionellid events are in light type. See text for details on zonation schemes and correlations between biostratigraphies and the geomagnetic polarity timescale.

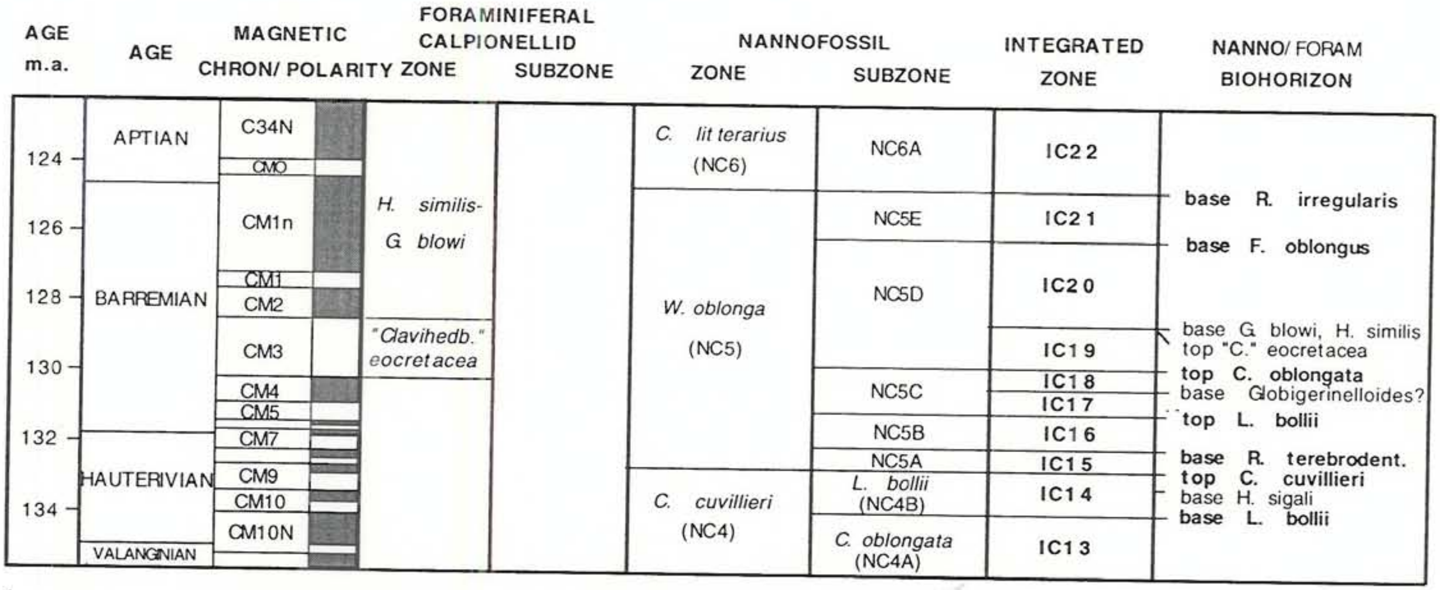

FIG. 5.—Integrated microfossil zonation for the Hauterivian through Aptian interval. Zonal markers are shown on the right. Nannofossil events are in bold type; planktonic foraminiferal events are in light type. See text for details on zonation schemes and correlations between biostratigraphies and the geomagnetic polarity timescale.

Interior macrofossil zones and European stage boundaries are indirect (e.g., see discussion in Hancock and others, 1993). This results from the rather different assemblages found in these two distant regions. In order to address this problem, we collected detailed samples from fourteen of the seventeen original Obradovich and Cobban (1975) localities and processed them for standard calcareous nannofossil biostratigraphic analysis. In all, some 470 samples were processed. Of these, less than ten percent (40) were nannofossiliferous. The results are compiled in Table 1. Seven localities were datable. Locations 2, 3, 4, 8, 9, 12, and 17 were sampled but found to be almost entirely barren of nannofossils and therefore are not discussed further. Fossiliferous sequences have been correlated with the zonation scheme of Roth (1978) and Sissingh (1977) and thereby more directly with the European stage stratotypes (Fig. 3). Key markers are listed in Table 1. The correlations with zonations are

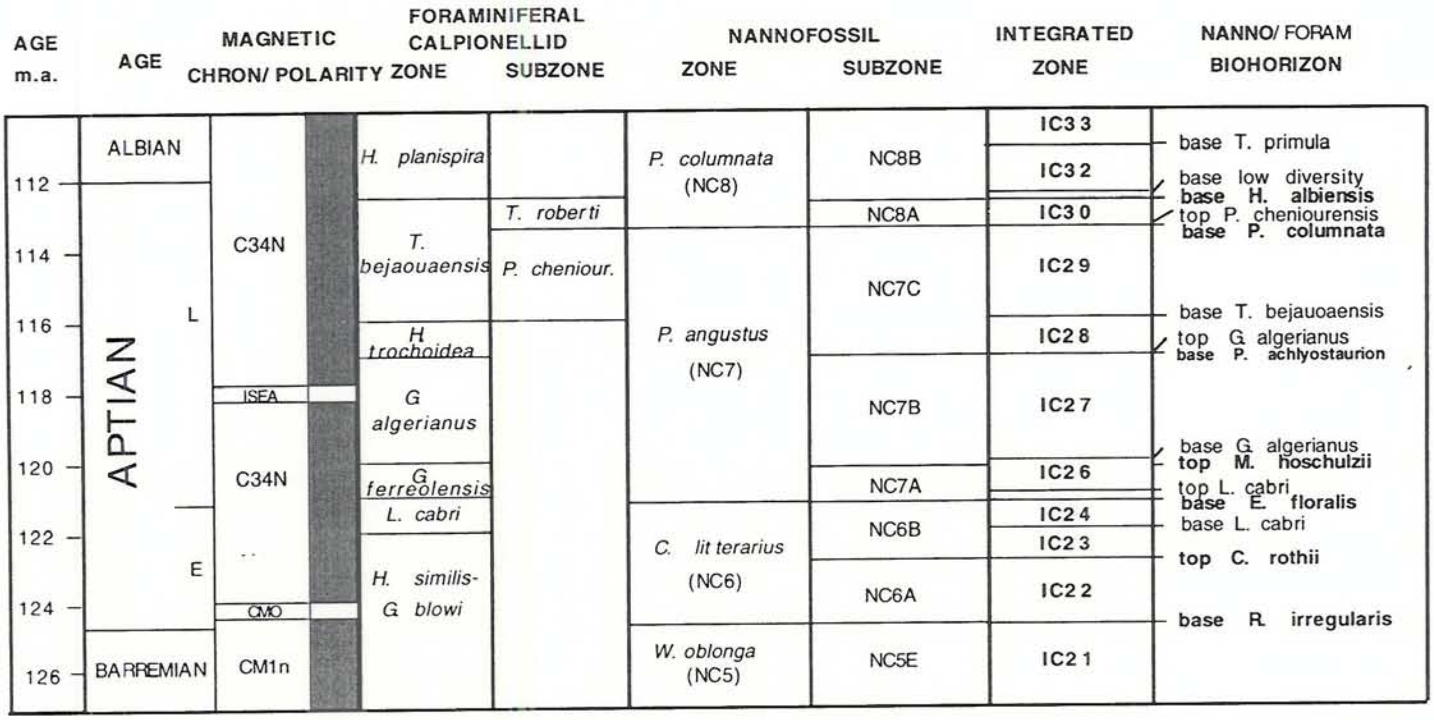

Fig. 6.—Integrated microfossil zonation for the Aptian interval. Zonal markers are shown on the right. Nannofossil events are in bold type; planktonic foraminiferal events are in light type. See text for details on zonation schemes and correlations between biostratigraphies and the geomagnetic polarity timescale.

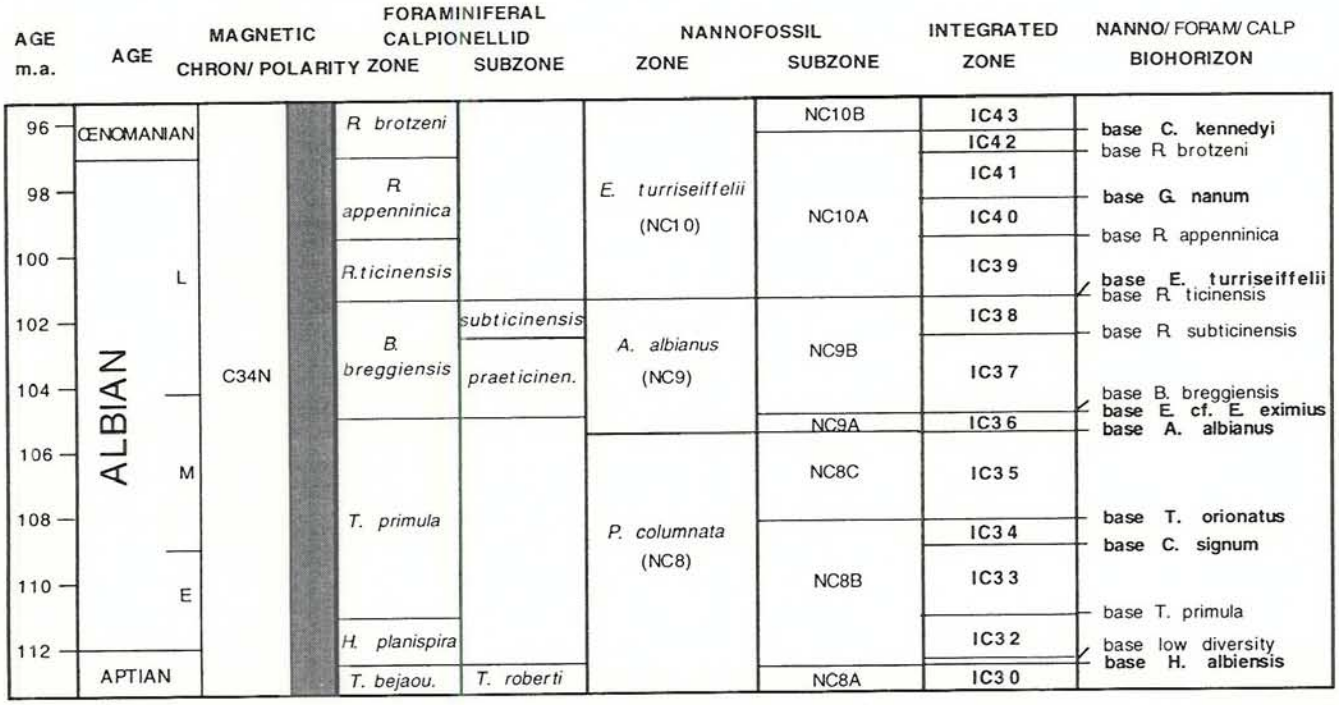

Fig. 7.—Integrated microfossil zonation for the Albian interval. Zonal markers are shown on the right. Nannofossil events are in bold type; planktonic foraminiferal events are in light type. See text for details on zonation schemes and correlations between biostratigraphies.

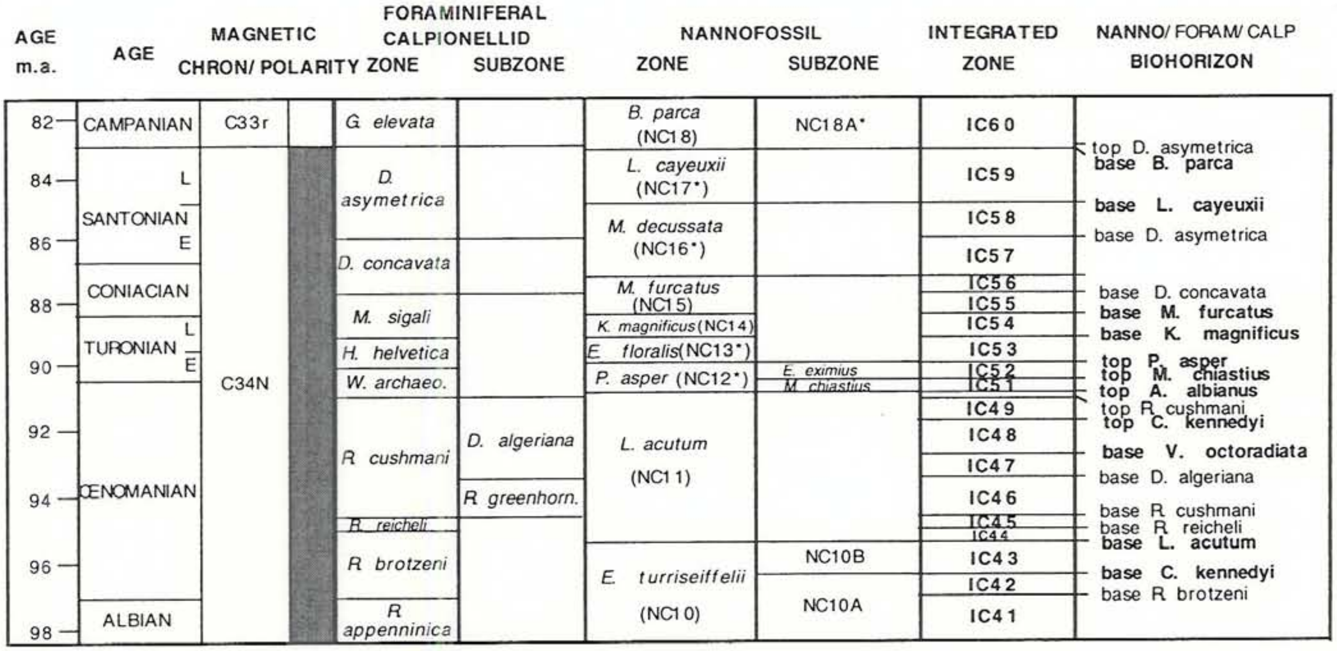

Fig. 8.—Integrated microfossil zonation for the Cenomanian through Santonian interval. Zonal markers are shown on the right. Nannofossil events are in bold type; planktonic foraminiferal events are in light type. See text for details on zonation schemes and correlations between biostratigraphies and the geomagnetic polarity timescale.

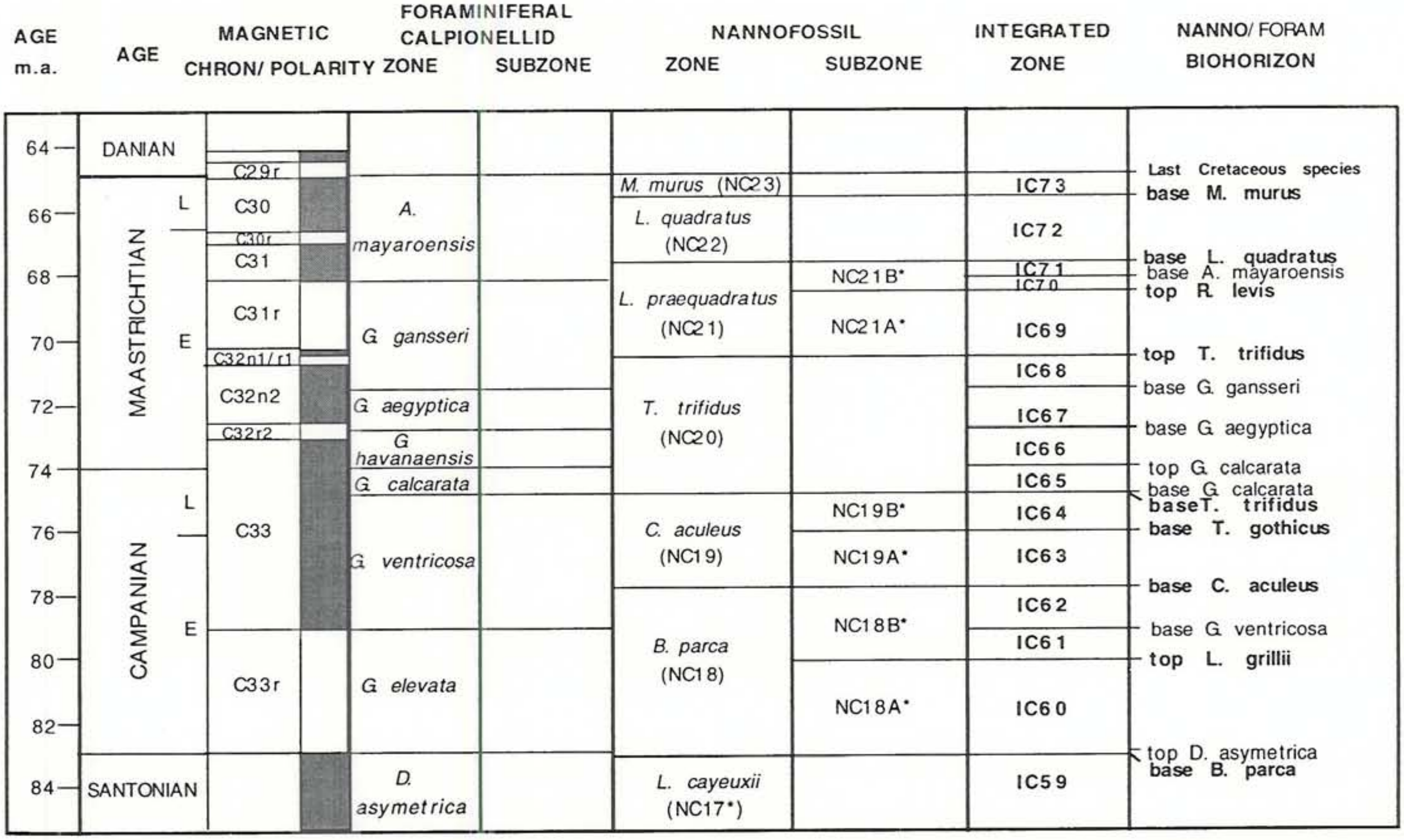

Fig. 9.—Integrated microfossil zonation for the Campanian and Maastrichtian interval. Zonal markers are shown on the right. Nannofossil events are in bold type; planktonic foraminiferal events are in light type. See text for details on zonation schemes and correlations between biostratigraphies and the geomagnetic polarity timescale.

straight-forward with one exception: the informal taxon *Broinsonia "preparca"* is a form which is smaller (5–6 µm long) than true *B. parca* and has a minuscule central area. This form occurs just below the first *B. parca* in two ODP sequences (Holes 762C and 763B) from the Exmouth Plateau (Bralower and Siesser, 1992). Perfect agreement with the published stage assignments occurs in three cases (Locations 11, 15, and 16; Table 1). In two cases (Locations 13 and 14), minor differences between the stage assignments predicted by nannofossils and by macrofossils (Obradovich and Cobban, 1975; Obradovich, 1993) may arise from uncertainty in the correlation of our sample set to the dated bentonites; in these localities the exact pyroclastic horizon dated was uncertain to us. Two upper Campanian levels (Locations 5 and 7) may have been placed slightly too low with respect to the Campanian/Maastrichtian boundary. Samples from around these levels contain an assemblage with *B. parca, Eiffellithus eximius, Reinhardtites anthophorus*, and *Arkhangelskiella cymbiformis*. We have not differentiated species of *Reinhardtites* (*R. anthophorus* and *R. levis*). This problem is discussed by Burnett and others (1992), but we have been unable to separate with the light microscope differences among these taxa which are primary from those which are diagenetic. Therefore, we cannot utilize these taxa in dating Campanian-Maastrichtian sediments with the exception of the last occurrence of the genus (e.g., Bralower and Siesser, 1992; see above). No specimens of *Quadrum trifidum* have been observed in these locations. The taxonomy and biostratigraphy of the nannofossil genus *Arkhangelskiella* is fraught with uncertainties. The specimens of *A. cymbiformis* observed here are well preserved with a fairly reduced central area size and few (15–20) pores in the central area, and are clearly differentiatable from *A. speciallata* (which first occurs in the lower Campanian; Perch-Nielsen, 1985) and *B. enormis*. The first occurrence of such clear specimens of *A. cymbiformis* has been observed only in Maastrichtian units in Europe (Sissingh, 1977; Perch-Nielsen, 1985) and other locations in the Western Interior Basin (D. Watkins, pers. commun., 1993). However. similar specimens have been identified co-occuring with *Q. trifidum, B. parca*, and *E. eximius* in sediments of the upper Campanian of the Exmouth Plateau (Bralower and Siesser, 1992). Thus the co-occurrence of *A. cymbiformis* with *B. parca* (last occurrence in lower Maastrichtian) and *E. eximius* (last occurrence close to Campanian/Maastrichtian boundary; Thierstein, 1976) at Locations 5 and 7 suggests rather indirectly that these two levels are in the uppermost Campanian. A conclusive solution of this question must await an in-depth study of the range of *A. cymbiformis* in northern European sections. It is clear from the range of this taxon described by Burnett and others (1992) that these authors have much wider taxonomic concepts than those utilized here. The macrofossil definition of the Campanian/Maastrichtian boundary has been the topic of much previous discussion (e.g., Kennedy and others, 1992) and is currently under close scrutiny (Premoli Silva and Sliter, unpubl. data). Thus, even though the zonal correlations should remain firm, the implications of our findings on the age of the Campanian/Maastrichtian boundary may change.

Besides more direct correlation with the European stage stratotypes, calcareous nannofossil biostratigraphy provides direct ties between the bentonite ages and the Geomagnetic Polarity Timescale (GPT). Correlation of nannofossil datums, the Sissingh (1977) and Roth (1978) zonation schemes, and the GPT as discussed in detail by Bralower and Siesser (1992) is shown in Figure 3. These correlations are not without problems, and different solutions have been described (e.g., Premoli Silva and Sliter, unpubl. data). However, our results allow two direct tie points, 75.3 Ma (the average age between locations 5 and 7) and the top of Chron C32R, and 83.8 Ma and the top of the long normal interval, C34N. Clearly much further work is required to refine many of these correlations, and for this reason we have not applied the correlations of nannofossil zones and isotopic ages and their implications to the GPT in the integrated biostratigraphy proposed here.

AN INTEGRATED CRETACEOUS MICROFOSSIL BIOSTRATIGRAPHY

Construction of the integrated microfossil scheme follows the correlation between the three microfossil biostratigraphies illustrated in Figure 1. The chronology of Harland and others (1989) is used for the ages of magnetic chrons and stage boundaries (with the exception of the Hauterivian/Barremian boundary, which has been moved to Chron CM4 according to the results of Cecca and others (1994)) and thus is assigned an age of 130.6 Ma instead of 131.8 Ma in Harland and others (1989). Microfossil-magnetostratigraphic correlations are used to place events within the chronology in the Lower Cretaceous M-sequence and the Upper Cretaceous reversed polarity interval. The ages of events within the Cretaceous long normal polarity interval are determined by relative sedimentary thicknesses in European land sequences (Tornaghi and others, 1989; Premoli Silva and Sliter, unpubl. data). The integrated scheme utilizes all potential markers except where two markers lie close to one another. In these cases the event which is more widely applicable is utilized. Zones are numbered from the base of the Berriasian stage upwards and given a prefix of IC (Integrated Cretaceous). Seventy three zones have been defined in this way (Table 2; Figs. 4–9). We stress that this is an informal scheme (ie, we have not defined zonal units formally as recommended by the International Subcommission on Stratigraphic Classification (Hedberg, 1976). In addition, since uncertainties remain with the correlations between the microfossil groups, we stress that this zonation can be entirely replaced by updated schemes in the future.

CONCLUSIONS

An informal, integrated, calcareous nannoplankton, calpionellid, and planktonic foraminifer biostratigraphy is proposed for the Cretaceous Period. This biostratigraphy consists of 73 zones and is based upon a literature survey of numerous DSDP/ODP and land sections as well as our own investigation of several of these sequences. The integrated scheme is most applicable in mid- and low-latitude sites and significantly increases potential biostratigraphic resolution to between 0.5 and 1.5 my/zone.

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