

NANNOFOSSILS AND UPPER CRETACEOUS (SUB)-STAGE BOUNDARIES - STATE OF THE ART

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Abstract: An integrated study of primarily nannofossil and macrofossil biostratigraphies (with some planktonic foraminifera biostratigraphy, chemostratigraphy and magnetostratigraphy) around numerous potential Upper Cretaceous stage and substage boundary sections, from a variety of geographical locations, has been in train since 1988. This project was devised in response to the discussions held at the original *Symposium on Cretaceous Stage Boundaries*, held in Copenhagen in 1983 by the Subcommittee on Cretaceous Stratigraphy, and a subsequent 'call for help' by Dr. K. (von Salis) Perch-Nielsen (1986), in both of which some potential boundary-stratotypes were identified. Most of these sections have been examined in detail, in addition to numerous others. The work has been, and still is being, carried out in collaboration with Dr. W.J. Kennedy (Oxford), Prof. A.S. Gale (Greenwich/NHM), Prof. J.M. Hancock (ICL), and others.

An integrated approach was applied to these studies in order to overcome correlation problems at stage boundaries. Although there was a strong historical precedent for macrofossil events to be used to officially define the Upper Cretaceous stage and substage boundaries, macrofossils cannot be used to directly date the majority of boreholes, nor any of the cores drilled by the Deep Sea Drilling Project nor the Ocean Drilling Program. In the oceans, nannofossils and planktonic microfossils are, and have been, extensively used for dating and correlation due to their small size, high abundance and wide geographical coverage. Complications have arisen in the past, with respect to correlation and boundary definitions in shelf and oceanic sediments, because of this situation: unfortunately, it is already the case that we have an unofficial system of stage boundaries defined on macrofossils for onshore sequences, and ones based on nannofossils and microfossils for the oceans. Thus, in order to precisely define a stage boundary, and, importantly, to be able to correlate it, it was viewed as imperative that the stratigraphies of a number of important fossil groups were precisely integrated.

These studies have integrated the biostratigraphies of nannofossils and macrofossils across potential stage and substage boundary stratotypes (Albian/Cenomanian to Maastrichtian/Palaeocene) around the world. The chosen sequences represented all palaeobiogeographical regions. Thus, the discrepancies between macrofossil and nannofossil approximations for potential stage boundaries has been largely overcome. The nannofossil results are presented here in summary and in the context of the provisional proposals for stage and substage boundaries determined by the various Working Groups at the second *Symposium on Cretaceous Stage Boundaries*, held in Brussels, in September, 1995. More detailed works, which will incorporate nannofossil range-charts for all of the Upper Cretaceous stage and substage boundary stratotypes in relation to the other stratigraphical events, are in preparation (Gale, Kennedy, Hancock & Burnett, and combinations thereof). Proposals and data based on the results of many of these studies were presented, both at the Working Group sessions and as a poster, at the second *Symposium on Cretaceous Stage Boundaries* and at the sixth *International Nannoplankton Association Conference* (Copenhagen, September 1995).

Introduction

In response to the discussions held at the original *Symposium on Cretaceous Stage Boundaries* (Copenhagen, 1983) and comments made by Perch-Nielsen (1986), the British Natural Environment Research Council (NERC) funded an extensive research program which would provide integrated macrofossil, microfossil and nannofossil biostratigraphical, and Sr-, O- and C-isotope chemostratigraphical event sequences across Upper Cretaceous stage and substage boundaries (Albian/Cenomanian to Maastrichtian/Palaeocene) for a variety of geographical locations. The aims of these studies were to (i) provide an integration of stratigraphic scales for the Upper Cretaceous, (ii) provide more-accurate and higher-resolution biostratigraphic scales for the Upper Cretaceous, (iii) improve and/or effect correlations between onshore and oceanic sequences, and thus (iv) propose the most useful stage boundary events and stratotypes for the Upper Cretaceous. By using an integrated approach, the research team was able to overcome certain problems associated with simple, second-order correlation studies, which necessarily incorporate a degree of error (sadly, some of which the author has seen reproduced in Working Group discussion documents). In examining a

number of sections per stage boundary, the team was able to first evaluate the correlatability of events over wide geographical areas before proposing the best candidates for Global Stratotype Sections and Points (GSSPs), as per the requirements of the Subcommittee on Cretaceous Stratigraphy.

Although a number of publications have already resulted from this program, further manuscripts are in preparation which particularly document the nannofossil data from the studied sections. Many of our data, therefore, have not yet been published, and none of it has been combined to provide a complete view. One aim of the present document is to provide a summary overview of both the published, in press and in preparation nannofossil work, the details of which will be used to formulate a new, high-resolution nannofossil zonation for the Upper Cretaceous which will incorporate the flexibility of being applicable to high- and low-latitude sediments (Burnett in prep., a).

Nannofossils and stratigraphic utility

Nannofossil events do not appear to have been regarded as very useful at the 1983 Symposium, ammonites and foraminifera being to the fore, and no chapter dedicated to

nannofossils appeared in the conference volume (*Bulletin of the Geological Society of Denmark*, 33(1/2), 1984), although Perch-Nielsen (1983) contributed to the abstracts volume. One aim of this paper is to provide an overview for nannopalaeontologists and others on the status of nannofossil events at Upper Cretaceous (sub-)stage boundaries, in order to redress the balance of the earlier meeting and to provide a firm basis for future biostratigraphical and correlative work.

As nannopalaeontologists know, nannoplankton are, and have been since the Late Triassic, planktonic and geographically widespread. Their planktonic habit has made them less susceptible to sea-level fluctuations than most macrofossil groups. Their cosmopolitan distribution, and their high diversity even in sub-polar regions, has provided them with great correlation potential, some of which persisted even at times of heightened provincialism (e.g. Burnett, 1990; Watkins *et al.*, in press; Burnett, in prep. b, c). Their abundance in sediments, and the closely-spaced sampling approach adopted by most nannopalaeontologists, means that first appearance datums (FADs) and last appearance datums (LADs) can be fairly accurately determined, as opposed to macropalaeontologists, who deal with far fewer specimens and lower sample frequencies and who, therefore, cannot be certain of detecting true FADs or LADs. (*N.B.* The FAD and LAD are distinct from the first and last occurrence of a taxon (FO, LO), which may be specific to a particular section, and may thus have no global relevance.) During the research program, it was continually underlined that there were major problems associated with correlating between disparate macrofossil zones, and particularly between the Boreal and Tethyan Realms (*i.e.* between belemnites and ammonites). In such cases, nannofossils proved their efficacy as correlative tools.

Nannofossils are generally 1-30 µm in length/diameter, which makes them ideal for dating borehole sequences, e.g. for the oil industry and the Ocean Drilling Program (ODP), situations in which macrofossils are mostly lacking. In order to provide a truly global relevance for any designated GSSP, the GSSP should be correlatable with oceanic sequences. Thus, there is a very real need for such GSSPs to incorporate some definition in terms of nannofossils. It is unfortunate that, at present, even though the majority of ODP authors use the 'cosmopolitan' nannofossil biozonation scheme originally devised from stage-stratotype (and other) material by Sissingh (1977) and supplemented by Perch-Nielsen (1979, 1983, 1985), and even though the biozones have consequently been directly correlated with stages and the majority of nannofossil events shown not to fall exactly at the commonly-used, but unofficial, (macrofossil-defined) stage boundaries, in oceanic material the nannofossil events are often taken to define, rather than approximate, stage boundaries. This introduces a primary correlation error between the oceans and shelves, and between nannofossil biozones and other fossil biozones. Workers using other fossil groups, or other dating methods, tend to understand the concept of the stage rather than the specifics of the nannofossil biozone (*i.e.* one tends not to be *au fait* with other biozonation schemes). Thus, they use the stage interpretation for correlating their own results with, or discussing their results in

relation to. On the surface this may seem trivial but, as an example, the author has been involved in some heated discussion concerning the dating of industrial borehole sequences, wherein the stage indicated by nannofossils was not the stage indicated by another microfossil group. The problem was not due to inaccurate biozonation by either party, but simply that the biozonation for one fossil group had not been directly correlated with the stage stratotype, such that the stages assigned to the zones could be described as arbitrary. When you consider that such apparent discrepancies are then passed on to people with little or no biostratigraphical background (this happens in academia, too), who have no idea how to interpret such apparent errors, it does become important. Is it any wonder that second-order correlation-of-everything charts, with such inaccuracies built in, tend not to work? Even worse, such charts portray a confidence in correlation which any expert will admit is, as yet, unfounded.

So, although not necessarily advocating the use of any particular nannofossil event as a boundary marker, it was seen as absolutely vital that GSSPs were defined with a clear knowledge of the associated nannofossil events. The success/failure of transmission of this point of view to other members of the Stage Boundary Working Groups at Brussels will eventually become apparent!

Upper Cretaceous nannofossil biozonation and stage boundaries - a historical perspective

In 1977, Sissingh published the second nannofossil zonation scheme for the entire Cretaceous (Thierstein published a more rudimentary one in 1976), introducing 26 numerical zones based on observations made from stage-stratotype material and sequences elsewhere in France, and also from Denmark (sidewall cores?), western Germany, The Netherlands, Oman (sidewall cores), western Tunisia (Dyr el Kef), Turkey (sidewall cores), the UK and North Sea, and the eastern USA. He also correlated the Upper Cretaceous portion with planktonic foraminifera zones (Sissingh, 1978). Previous schemes existed for parts of the column, based on geographically-limited observations: Sissingh (1977) and Perch-Nielsen (1979, 1985) have provided overviews of these. The events used by Sissingh (1977) mirrored these earlier observations to an extent, but some of the earlier observations are now known to be either erroneous or ephemeral. Thus, Sissingh's scheme stands as a commonly-used framework, although it is not without its problems, either. Certain of these are discussed below but basically stem from his use of many low-latitude taxon events (derived from the Tunisian sequence), and possibly his apparently erratic sampling methods (he examined mainly spot-samples from the type sequences). Perch-Nielsen (1979, 1983, 1985) supplemented Sissingh's (1977) biozones with her own (from the North Sea to the Mediterranean) and a variety of others' observations, and highlighted the fact that certain of Sissingh's biozones were not applicable in Boreal areas.

Surprisingly few nannopalaeontologists have worked on material from the Upper Cretaceous type areas (the published work is summarised below), or have integrated nannofossil events with other fossil events. Data from those that have has mostly been published in a sum-

marised format, rather than as detailed stratigraphical distribution charts. Consequently, it is virtually impossible to glean enough information from published sources to facilitate further resolution of the Sissingh/Perch-Nielsen biozonation, nor to check the validity of potential new nannofossil events for a global zonation scheme. Perch-Nielsen (1985) commented that Upper Cretaceous coccolith zones have repeatedly been correlated with the classic stages but that the preservation of coccoliths in the stage-stratotypes is variable and that "correlations have had to be made via other fossils with the evident possibilities of shifting boundaries higher or lower depending on one's own preferences, tradition or wishful thinking" (p.340)! This has demonstrably been the case, such that there is still no consensus between current workers. It is hoped that the proposals put forward by the Brussels Working Groups, and acceptance of these at the Beijing *International Geological Congress* in August, 1996, will filter through our science rapidly and change this situation for the better.

The Cenomanian type section is represented in and around Le Mans, Sarthe (NW France). The nannofloras of the Marnes de Ballon ('Lower' Cenomanian) and the Craie de Théligny ('Middle' Cenomanian), both close to Le Mans, were described by Verbeek (1976). He used the FADs of *Eiffellithus turriseiffelii*, *Lithraphidites alatus* and *Gartnerago obliquum* to subdivide the stage. The Cenomanian nannoplankton of Ballon and Ste. Ulphace-Théligny-Moulin de l'Aunay were investigated by Sissingh (1977). He was able to assign one nannofossil zone to the sections (CC9), based on the FAD of *Eiffellithus turriseiffelii*, but his other Cenomanian marker event, the FAD of *Microrhabdulus decoratus*, was absent from these sections (the reference section for the zone is in Tunisia). This latter event has been found to be highly diachronous by the author. Sissingh (1977) noticed that predominantly Tethyan, e.g. Tunisian, Late Cretaceous nannoplankton assemblages were generally more diverse than more northerly, European (e.g. northern France) assemblages, the latter being characteristically dominated by solution-resistant forms, a point also noted by Verbeek (1977). Verbeek (1977) proposed the utilisation of the FAD of *Lithraphidites acutus* between the FADs of *Eiffellithus turriseiffelii* and *Microrhabdulus decoratus* in the 'Middle' Cenomanian. Manivit *et al.* (1977) used the LAD of *Hayesites albiensis* and the FAD of *Lithraphidites acutus* as datums in the 'Middle' Cenomanian of the Théligny section. The *Lithraphidites acutus* event is commonly substituted for the FAD of *Microrhabdulus decoratus*, and this is followed by the author. Manivit *et al.* (1977) also utilised the LAD of *Microstaurus chiastius* to subdivide CC10 (from the FAD of *Lithraphidites acutus*), and this event has been found to be widely applicable.

Perch-Nielsen (1979, 1983, 1985) placed the LAD of *Crucicribrum anglicum* at the same level as the LAD of *Hayesites albiensis*, at the base of CC9B. At the proposed boundary stratotype, Mont Risou, *Crucicribrum anglicum* was found to range from near the base of the uppermost MF subzone of the Albian in CC9B to at least the Lower Cenomanian (CC9C). She also used the FAD of *Corollithion kennedyi* to further subdivide CC9, but placed this event at the same level as the LADs of *Watznaueria*

britannica and *Braarudosphaera africana*. These events occur above the *Corollithion kennedyi* FAD at Mont Risou.

Birkelund *et al.* (1984) indicated that the FAD of *Eiffellithus turriseiffelii* occurred slightly below the FAD of *Hypoturrilites schneegansi* (ammonite) and above the LAD of *Planomalina buxtorfi* (PF). Gale *et al.* (in press, a) found *Eiffellithus turriseiffelii* to be present well below the FAD of *Mantelliceras mantelli* (their proposed ammonite boundary event, which now, technically, lies just above the boundary), and well below the LADs of *Planomalina buxtorfi* (PF) and *Hayesites albiensis*. In fact, the FAD of *Eiffellithus turriseiffelii* was not identified in the interval studied at Mont Risou (*i.e.* its FAD lies at least 110m below the boundary there).

The type area for the Turonian is between Saumur and Montrichard, around Tours (NW France). Manivit (1971) studied the 'Lower' Turonian at Château-du-Loir (NW of Tours) and at Amboise and Fréteville (E of Tours), and the 'Middle' Turonian of Ste.-Maure-de-Touraine (S of Tours) and Ponce-sur-le-Loir (N of Tours) but did not include stratigraphical distribution charts of specific sections, incorporating the data, instead, into stage-by-stage nannofossil occurrences. She used the FADs of *Gartnerago obliquum* and *Corollithion exiguum* to apply nannofossil zones to the Turonian type succession, and correlated these events with the Calycoceras naviculare and Acanthoceras bizeti Ammonite Zones (Upper Cenomanian to Middle Turonian), respectively. Both nannofossil events are now known to occur stratigraphically lower. Sissingh (1977) studied sections along the Cher Valley (E of Tours). He indicated that the FAD of *Quadrum gartneri* almost coincided with the 'base' of the Turonian, and that *Lucianorhabdus maleformis* (the FAD of which he used as a marker in the Turonian, CC12) was not present in the Turonian of the Cher Valley. *Lucianorhabdus maleformis* has proved to be unreliable as a marker, and the FAD of *Eiffellithus eximius* is often substituted for it. This is followed by the author. Manivit *et al.* (1977) found *Quadrum gartneri* to occur in the 'Lower' Turonian of Fréteville. Work by Manivit with Zeighampour (*in Robaszynski et al.*, 1982), on outcrops in the Saumurois area and a well at Civray-de-Touraine, resulted in the FAD of *Quadrum gartneri* being placed in the Lower Turonian Mammites nodosoides Ammonite Zone. The FAD of *Lucianorhabdus maleformis* was found to occur towards the top of the Kameronoceras turoniense Ammonite Zone ('Middle' Turonian), and the FAD of *Eiffellithus eximius* in the Romaniceras kallei Ammonite Zone ('Middle' Turonian). (*N.B.* In Robaszynski (1983), the FAD of *Eiffellithus eximius* is shown to occur in the R. ornatisimum Ammonite Zone.) Manivit (*op. cit.*) concluded that the type area's nannofloras were similar to those found in north, south and south-eastern France.

The Cenomanian/Turonian boundary is characterised in many locations (shelf and oceanic, Boreal to Austral regions) by hiati, condensation and black shales, the result of an extensive oceanic anoxic event. This event is explored in biostratigraphical detail by Bralower (1988) and Jarvis *et al.* (1988).

Birkelund *et al.* (1984) indicated that the FAD of *Quadrum gartneri* was "widely recognisable" (p.12) and

FIGURE 1: COMPARISON OF STAGE- BOUNDARY DEFINITIONS AND NANNOFOSSIL ZONES

NANNOFOSSIL BIOZONATION AND APPROXIMATE STAGE BOUNDARIES after Sissingh (1977, 1978) & Perch-Nielsen (1979, 1983, 1985)		PROPOSED STAGE BOUNDARIES after Brussels Working Groups, 1995	
STAGE (APPROXIMATE)	CC SUBZONE	CC ZONE	STAGE (PROPOSED)
upper Upper Maastrichtian	B	26	uppermost Maastrichtian
	A	25	
Upper Maastrichtian	C	24	Upper Maastrichtian
	B	23	
	A	22	
Lower Maastrichtian		21	
Lower Maastrichtian to uppermost Campanian	B	20	
	A	19	
upper Upper Campanian	C	18	Upper Campanian (Tethyan)
	B	17	
	A	16	
lower Upper Campanian		15	
upper Lower Campanian	B	14	
	A	13	
Lower Campanian	C	12	Lower Campanian (Tethyan)
	B	11	
	A	10	
Lower Campanian/ Upper Santonian		9	
Upper Santonian		8	Upper Santonian
		7	Middle Santonian
upper Lower Santonian		6	Lower Santonian
Lower Santonian to Upper Coniacian		5	Upper Coniacian
		4	Middle Coniacian
		3	Lower Coniacian
Lower Coniacian	B	2	Upper Turonian
	A	1	
lower Lower Coniacian to Upper Turonian		0	Middle Turonian
Middle Turonian to upper Upper Cenomanian		-1	Lower Turonian
Upper Cenomanian	B	-2	Upper Cenomanian
	A	-3	Middle Cenomanian
		-4	Lower Cenomanian
Lower Cenomanian to Upper Albian (pars.)	C	-5	
	B	-6	
	A	-7	Upper Albian (pars.)

lay within the Neocardioceras juddii Ammonite Biozone (Upper Cenomanian). The author found the event in the Plenus Marls/Metoicoceras geslinianum Ammonite Zone (Upper Cenomanian) in S and NE England. At Rock Canyon, near Pueblo, Colorado (the proposed boundary stratotype), Watkins (1985) apparently identified its FAD in the Watinoceras devonense Ammonite Biozone (Lower

Turonian), whilst Bralower (1988, Figure 16) found it in the Metoicoceras mosbyense Ammonite Biozone which lies below the Sciponoceras gracile Ammonite Biozone (Upper Cenomanian) (Cobban *et al.*, 1995). Therefore, the FAD is placed in the Upper Cenomanian.

The area around Cognac, Charente (W France) represents the Coniacian type area. Manivit (1971) studied the type Coniacian at Cognac, and utilised the FADs of *Marthasterites furcatus* (CC13) and *Kamptnerius magnificus* to identify the stage here. Both species are now known to occur stratigraphically below the base of this stage. The *Marthasterites furcatus* event was found in the top of the Coniacian Micraster cortestudinarium Echinoid Zone, according to Manivit (1971). Sissingh (1977) also examined the Coniacian of Cognac but did not find *Marthasterites furcatus*, whilst Robaszynski (1983) indicated that *Marthasterites furcatus* was found in the Peroniceras tricarinarum Ammonite Zone of the Turonian type area. Sissingh (1977) used the FAD of *Micula staurophora* to define the Upper Coniacian (CC14).

Birkelund *et al.* (1984) stated that the FAD of *Marthasterites furcatus* was a "world-wide marker... which is generally used by nannofossil specialists as the basal...[event]...of the Coniacian" (p.13-14), although Bailey *et al.* (1984), in the same volume, indicated that the event lay in the Subprionocyclus neptuni Ammonite Biozone (Upper Turonian) in the UK and Germany. The author has found *Marthasterites furcatus* to be virtually useless as a biostratigraphic indicator in many geographical areas: its geographical and stratigraphical distributions are patchy at best outside of the Tethyan Realm, such that one can never be sure of identifying its true FAD. In S England, the author found *Marthasterites furcatus* in the Sternotaxis planus Echinoid Biozone ('Upper' Turonian), whilst Crux (1982) found it below this in the Terebratulina lata Brachiopod Biozone ('Mid' or 'Upper' Turonian). In the Salzgitter-Salder section (the proposed boundary stratotype), *Marthasterites furcatus* is present at least from below *Didymotis* Event I (Bed 38b, Upper Turonian; Burnett in prep., d); the FAD of *Lithastrinus septenarius* was found from Bed 42a, below the proposed boundary. This latter event was used by Perch-Nielsen (1979, *etc.*) to subdivide CC13.

The Santonian type area is around Saintes, Charente (W France). The nannofloras of Cognac and Chateaubernard (SE of Saintes) were studied by Manivit (1971). She assigned one zone to the stage, using the FADs of *Kamptnerius magnificus* and *Broinsonia parca parca* to define it. The former event is in the Turonian, the latter in the Campanian. Sissingh (1977) investigated the Santonian of Saintes and of Javresac and Ste. Laurent-Louzac (SE of Saintes). *Micula staurophora* (CC14) was present, and he also used the FADs of *Reinhardtites anthophorus* (CC15) and *Lucianorhabdus cayeuxii* (CC16) to define two nannofossil zones within the stage, although there appeared to be a reversed succession in the type area (rare *Lucianorhabdus cayeuxii* were believed to occur below the stated FAD datum, although these could possibly be ascribed to either *Lucianorhabdus quadrididus* or *Acuturris scotus*). Verbeek (1977) produced a nannofloral distribution chart from the type section, which included

Micula staurophora. He used the FADs of *Placozygus fibuliformis* and *Broinsonia parca parca* to characterise the 'Middle' to Upper' Santonian in the type area.

Reinhardtites anthophorus appears to evolve from *Zeughrabdotus sisypus* (= *Z. scutula*), or similar forms, and thus its FAD may vary between authors with differing concepts of the taxon. It may, therefore, seem to first occur before the FAD of *Micula staurophora* due to this reason, or one (both?) of these markers may be diachronous. However, *Reinhardtites anthophorus* often first occurs in association with *Lithastrinus grillii*, as noted by Perch-Nielsen (1979), an event which can be used as confirmation of, or possibly a substitute for, the datum. She also reported the coincident FAD of *Lucianorhabdus cayeuxii* with the LAD of *Lithastrinus septenarius*. However, the latter event has been found to predate the FAD of *Lucianorhabdus cayeuxii* in many locations.

Birkelund *et al.* (1984) made no mention of nannofossils in relation to the Santonian/Campanian boundary.

The Campanian type area lies around the Grande and Petite Champagne, northern Aquitaine (SW France). Manivit (1971) investigated sections at Ste.-L'Heurine, Gente and Archiac (S of Cognac), Talmont (on the north bank of the Gironde) and Aubeterre (S of Angoulême). She used the FADs of *Arkhangelskiella specillata*, *Ceratolithoides aculeus* (CC20) and *Lithraphidites quadratus* (CC25B, Maastrichtian) to subdivide the stage. She correlated the former two events with the Actinocamax quadratus/Placentoceras bidorsatum and Hoplitoplacentoceras vari/Belemnitella mucronata Macrofossil Zones, respectively.

Sissingh (1977) originally placed the Santonian/Campanian boundary at the first regular occurrence of *Calculites obscurus* (at the base of CC17) but revised this (Sissingh, 1978), placing the base of CC17 in the 'Upper' Santonian based on PF associations, remarking, however, that the Santonian/Campanian boundary still lay within CC17. He examined material from Gimeux (SW of Cognac), Gente, along the north bank of the Gironde from Royan to Ste.-Seurin-d'Uzet, Montmoreau (S of Angoulême) and Brossac (SW of Angoulême). Of the seven zones he erected for the Campanian, six were recognised in the type area. These were based on the FADs of regular *Calculites obscurus*, *Broinsonia parca parca* (CC18), *Ceratolithoides aculeus* (CC20), *Uniplanarius sissinghii* (CC21), *Uniplanarius trifidus* (CC22A-CC23B; the occurrence of which was sporadic, a finding duplicated by Verbeek's (1977) study of a section at Aubeterre, S of Angoulême), and the LADs of *Reinhardtites anthophorus* (CC22C) and *Tranolithus orionatus* (CC23B). The majority of these events are Tethyan and cannot be recognised in high-latitude areas. A large number of sections in the type area were sampled by Lambert (1980), including those between Royan and Beaumont (on the north bank of the Gironde) and between Saintes (to the NW) and Aubeterre (to the SE). He used the FADs of *B. parca parca*, *C. aculeus*, *Prediscosphaera stoveri*, *Lithraphidites praequadratus* and "*Tetralithus* sp." to divide the stage.

The FAD of *Broinsonia parca parca*, a virtually cosmopolitan event, was noted by Birkelund *et al.* (1984)

to be "used by coccolith specialists for definition of the [Santonian/ Campanian] boundary" (p. 16), although the taxon's FAD is actually well within the traditionally defined Campanian (Bailey *et al.*, 1984; Gale *et al.*, in press, b). Birkelund *et al.* (1984) also made comment that "this species is known to be diachronous" (p. 16). This, however, is relative to macrofossil datums which themselves may be diachronous! One problem noted at various locations by the author, however, and forming the crux of a brief presentation by Sylvia Gardin at the Working Group session, was the problem of correct identification of *B. parca parca* within the *B. parca* plexus. *Broinsonia parca parca* belongs to an evolutionary lineage (*Broinsonia parca expansa*-*Broinsonia parca parca*-*Broinsonia parca constricta*) which involves the gradual reduction in dimensions of the central area plate of the coccolith. In order to use this event correctly, a precise definition of the central area dimensions of the taxon must be determined in order to obtain the correct FAD. A biometric study on numerous sections containing the plexus is currently being carried out at UCL, which will form a basis for comparison with other studies.

The Campanian stage contains the endemic acme for Mesozoic nannofossils, at which time widespread correlation potential was reduced but diversity reached a peak (Bown *et al.*, 1991, 1992). Recent works have begun to overcome the intercorrelative problems associated with this interval (e.g. Burnett, 1990; Watkins *et al.*, in press; Burnett, in prep., b: the latter work in particular has managed to identify tie-lines between Indian Ocean sites at palaeolatitudes ranging from 18.9°S to 62.9°S for this interval).

Sissingh (1977) introduced the FAD of *Reinhardtites levis* as a subzonal marker event in the uppermost Campanian. This taxon evolved from *Reinhardtites anthophorus* by gradual closing of the central area, such that *Reinhardtites levis* possesses "very small or completely sealed openings" (p.47), transitional morphologies being represented through the Campanian. Unfortunately, these openings can also be closed by calcitic overgrowth. Additionally, *Reinhardtites levis* has been found to have diachronous FADs and LADs (Burnett, in prep., a), its FAD apparently transgressing from the Lower to the Upper Campanian, from certain low to high latitudes.

The type section for the Maastrichtian is in the ENCI Quarry, near Maastricht, Limburg (SE Netherlands). The lithostratigraphy of both this quarry and the Halembaye Quarry (near Visé, Liège, E Belgium) has been published by various authors (e.g. Felder *et al.*, 1980; Bless *et al.*, 1987). Sedimentation in this area was repeatedly interrupted, giving rise to numerous hardgrounds which facilitated lithological subdivision.

Bramlette & Martini (1964) examined three samples from the 'Upper' Maastrichtian of the ENCI Quarry but did not attempt to identify zonal indicators. Manivit (1971) was the first to apply nannofossil zones to this section, using the FADs of *Lithraphidites quadratus* (CC25B) and *Nephrolithus frequens* (CC26). She then attempted a correlation of these zones with ammonite zones, resulting in the emplacement of the *Lithraphidites quadratus* NF Zone in the *Bostrychoceras polyplocum* Ammonite Zone (Up-

FIGURE 2: SUMMARY OF WORKING-GROUP PROPOSALS FOR UPPER CRETACEOUS STAGE AND SUBSTAGE BOUNDARY EVENTS AND STRATOTYPES

arrows refer to (sub-)stage boundaries

ABSOLUTE AGE after Gradstein <i>et al.</i> (1994)	ABSOLUTE (⁴⁰ Ar/ ³⁹ Ar) AGE after Obradovich (1993)	STAGE	SUBSTAGE	BOUNDARY EVENT AMM = ammonite BEL = belemnite CRIN = crinoid INOC = inoceramid bivalve NF = nannofossil PF = planktonic foraminifer	AUXILIARY EVENT(S)	BOUNDARY STRATOTYPE AG = Andy Gale JH = Jake Hancock EK = Erle Kauffmann ML = Marcos Lamolda RM = Rory Morimore FR = Francis Robaszynski IP-S = Isabella Premoli-Silva K-AT = Karl-Armin Tröger CW = Chris Wood	COMMENTS & REFERENCES CONTAINING NANNOFOSSIL DATA	WORKING-GROUP CHAIRMAN full reports by the chairmen on the Brussels Working Group decisions will appear in the conference volume by summer, 1996
65.0±0.1Ma	65.4±0.1Ma	PAL.	LR				poor preservation of NFs & PFs makes this a poor stratotype choice, however, correlations can be made via Zumaya (NE Spain) & Bidart (SW France). Burnett in prep., e; Burnett <i>et al.</i> , 1992a, 1992b, 1992c; Hancock <i>et al.</i> , 1993; Jagt <i>et al.</i> , 1992; Kennedy <i>et al.</i> , 1995; McArthur <i>et al.</i> , 1992; Robaszynski <i>et al.</i> , 1985; Schönfeld & Burnett, 1991.	Dr. Gilles S. Odin, Dépt. Géologie Sédimentaire, Université Pierre et Marie Curie, 4 place Jussieu, Case 119A, F-75252, Paris Cedex 05, France
		MAAST- RICHTIAN	UP.	no decision, probably AMM event		no decision, probably Zumaya, NE Spain		
71.3±0.5Ma	71.3±0.5Ma		LR	FAD <i>Pachydiscus neubergicus</i> (AMM)	corresponds to FAD <i>Belemnella lanceolata</i> (BEL)	Tercis Quarry, SE France, @117m (in Bed N)		
		CAMPANIAN	UP.				insertion of 7th stage (?Dordognian) contemplated at top of Camp. due to long duration of Camp. & apparently complete Camp. stratotype. Burnett, 1990; Burnett in prep., e; Jagt <i>et al.</i> in press; Kennedy <i>et al.</i> , 1992; Kennedy & Hancock, 1995; Schönfeld & Schulz (Co-ords) <i>et al.</i> in press.	Prof. Jake M. Hancock, Dept. of Geology, Imperial College of Science & Technology, Prince Consort Road, London SW7 2BP, UK
			?MID.	no formal proposals, investigation underway into possibility of equal-duration, 3-fold subdivision	compatible with FAD <i>Platoniceras bidorsatum</i> (AMM). Links with PF (<i>Dicarinella asymetrica</i>), NF (<i>Broinsonia parca</i> lineage), & 34N/33R magnetostratigraphic boundary under investigation			
83.5±0.5Ma	83.5±0.5Ma		LR	LAD <i>Mersupites testudinarius</i> (CRIN)		no decision, either Waxahachie, Texas (AG/JH) or Seaford Head, Sussex, UK (RM/CW), IP-S co-ord.		
		SANTONIAN	UP.				Gale <i>et al.</i> in press, b; Gale <i>et al.</i> in prep., b.	
			MID.	no decision, probably FAD <i>Urtiacrinus socialis</i> (CRIN)		no decision (AG)		Dr. Marcos A. Lamolda, Universidad del Pais Vasco, Facultad de Ciencias, Estratigrafia y Paleontologia, Apartado 644, E- 48080, Bilbao, Spain
			LR	no decision, either FAD <i>Cordiceramus cordiformis</i> (INOC) or LAD <i>Cordiceramus undulatus</i> (INOC)		no decision (AG)	Kennedy <i>et al.</i> in press.	
85.8±0.5Ma	86.3±0.5Ma		UP.	FAD <i>Cladoceras undulotopiacatus</i> (INOC)	approximates FAD <i>Sigalia carpathica</i> (PF)	no decision, either 10 Mile Creek, Texas (AG/EK) or Olazagutia Quarry, Navarra, Spain (ML)	Gale <i>et al.</i> in prep., a; Kennedy, 1995c.	
		CONIACIAN	UP.	FAD <i>Inoceramus (Magdeceramus) subquadratus</i> group (INOC)	?corresponds to FAD <i>Gonioteuthis praewestfalica</i> (BEL)	no decision, either 10 Mile Creek, Texas (AG) or Seaford Head, Sussex, UK (CW)		Dr. Erle G. Kauffmann, Dept. of Geological Sciences, University of Colorado, Boulder, Colorado 80309- 0250, USA
			MID.	FAD <i>Volviceras koeneni</i> (INOC)	corresponds to FAD <i>Stensioina granulatagranulata</i> (ECH)	no decision, either Dallas, Texas (AG) or S England (CW)	expanded sequence, no ammonites but abundant other fossils, easy access to vertically-bedded strata: Wood <i>et al.</i> , 1984; Burnett in prep., d; Burnett <i>et al.</i> in prep., a; Kennedy, 1995b; Naji (in press).	
89.0±0.5Ma	88.7±0.5Ma		LR	FAD <i>Cremnoceras rotundatus</i> (INOC) of authors	corresponds to flood of <i>Inoceramus waltersdorfensis</i> <i>hannoversis</i> of authors (INOC) & <i>Didymotis</i> Flood Event II (INOC)	Salzgitter-Saider Quarry, Lower Saxony, N Germany, within base of Bed 45c		
		TUPONIAN	UP.	no decision, probably INOC event (WG of INOC workers to recommend datum)		no decision, INOC WG to recommend stratotype (K- AT)		Prof. Peter Bengtson, Geologisch- Paläontologisches Institut, Im Neuenheimer Feld 234, D-69120 Heidelberg, Germany
			MID.	FAD <i>Collignonoceras wooligari</i> (AMM)		Rock Canyon Anticline section, W of Pueblo, Colorado, base of Bed 120 in Bridge Creek Member, Greenhorn Limestone Formation	no condensation, lies in Milankovitch cycles correlatable over Western Interior, radiometrically- dated via associated bentonites. Bralower, 1986; Jarvis <i>et al.</i> , 1988; Robaszynski, 1983; Robaszynski <i>et al.</i> , 1982; Watkins, 1985.	
93.5±0.2Ma	93.3±0.2Ma		LR	FAD <i>Watnocras devonense</i> (AMM)	corresponds to FAD <i>Helvetoglobotruncana helvetica</i> (PF) & base of Bed 86, 50cm above FAD of <i>Mytiloides hattini</i> (INOC)	Rock Canyon Anticline section, W of Pueblo, Colorado, base of Bed 86 in BCM, GLF		
		CENOMANIAN	UP.	no decision, either FAD <i>Calyoceras guerangeri</i> (AMM) or FAD/LAD <i>Acanthoceras jukesbrownei</i> (AMM) or FAD <i>Inoceramus pictus</i> group (INOC) (FR)			expanded sequence containing well-preserved fossils, & NFs with both Boreal & Tethyan elements. A secondary reference section in the Tethyan Realm was proposed at Kalaat Senan, N of El Kel, Tunisia by Robaszynski and his group but it is likely that this sequence is condensed in part. Gale <i>et al.</i> in press, a; Kennedy, 1995a; Robaszynski <i>et al.</i> , 1993, 1994.	Prof. Dr. Karl-Armin Tröger, Bergakademie Freiberg, Institut für Geologie, Fakultät 3, Bernhard-von- Cotta Straße 2, 09596 Freiberg, Sachs., Germany
			MID.	FAD <i>Cunningtonoceras inermis</i> (AMM)	corresponds to FAD <i>Inoceramus schloendorfi</i> (INOC) & FAD <i>Rotalipora reicheli</i> (PF)	no decision, probably S France (FR)		
98.9±0.6Ma	98.5±0.5Ma	ALB.	UP.	FAD <i>Rotalipora globotruncanoides</i> (PF)		Mont Risou, near Rosens, Hautes-Alpes, SE France		

per Campanian) and the *Nephrolithus frequens* NF Zone in the *Pachydiscus neubergicus*/*Cidaris faujasi* Macrofossil Zone (Lower Maastrichtian). Sissingh (1977) also studied material from the type section. He utilised the LADs of *Tranolithus orionatus* (CC23B) and *Reinhardtites levis* (CC24), and the FAD of *Nephrolithus frequens* (CC26) to define his zones for the Maastrichtian. The poor preservation of the type material was commented on by Verbeek (1977), who used the FADs of *Lithraphidites quadratus* and *Micula murus* (CC25C) to define zones in this interval. Sissingh's (1977) material was reinvestigated by van Heck (1979), who did not attempt to reapply a nannofossil zonation. Čepěk & Moorkens (1979) also studied the ENCI Quarry stratotype, using *Lithraphidites quadratus* and *Nephrolithus frequens* as marker events. It is now known that the FAD of *Nephrolithus frequens* is highly diachronous and should be used with caution.

Verbeek (1983) restudied material from the ENCI Quarry, this time using *Nephrolithus frequens* as a zonal marker. A multidisciplinary study, undertaken by Robaszynski *et al.* (1985), included investigation of material from the Halembaye Quarry, in the type area. Manivit (*in Robaszynski et al.*, 1985) noted the largely Boreal influence on the nannofloras, and the good preservation, with only weak diagenetic effects on the specimens, of the material. She believed that the LADs of *Broinsona parca constricta*, *Eiffellithus eximius* and *Reinhardtites anthophorus* (used to indicate an approximation to the Campanian/Maastrichtian stage boundary in Tethyan areas), rather than being represented due to reworking, could here be of Upper Maastrichtian age, *i.e.* their LADs were diachronous. However, in the presence of so many hardgrounds, reworking of these events into younger sediments cannot be ruled out. Manivit (*op. cit.*) used the FADs of *Lithraphidites praequadratus* and *Lithraphidites quadratus* to subdivide the interval.

Birkelund *et al.* (1984) commented that the LAD of the "widespread" (p. 17) *Uniplanarius trifidus* "had been used to define the base of the Maastrichtian" but that the event was actually well within the Lower Maastrichtian. This event (and nannofossil) is Tethyan-restricted.

In summary, Figure 1 shows the most commonly-used biozonation scheme (after Sissingh and Perch-Nielsen, *op. cit.*) with Sissingh's stage approximations redefined according to the proposals put forward by the Brussels Working Groups and the author's data.

Nannofossil biozones are generally supposed to have been devised utilising easily-recognisable, frequently-occurring members of evolutionary lineages, with subzones supposedly based on taxa which do not necessarily fulfill these requirements. In these respects, the Sissingh/Perch-Nielsen scheme has been generally acceptable and useful. It seems, however, that the only way forward in nannofossil biozonation and correlation, as we learn more about palaeobiogeographical and palaeoecological constraints on spatial distributions and abundances of taxa, and as we become more aware of stage boundaries, is by ongoing refinement of their subzones. In order to achieve this, we must be prepared to start to utilise and incorporate anything that appears to have a reliable FAD or LAD, whether it is abundant or not, or biogeographically restricted or

not, but which can be correlated elsewhere, either directly or via sequences which contain mixed (*e.g.* high- and low-latitude) nannofloral elements derived from adjacent palaeobiogeographical provinces. This approach has been adopted by the author, and the proposed new zonation scheme (Burnett in prep., a) will incorporate this feature.

Upper Cretaceous (Sub-)Stage boundary proposals and nannofossils

The definition of Cretaceous stage boundaries is a momentous event! So far, all definitions have been unofficial. Once the proposals for GSSPs have been ratified, we will be obliged to redefine our nannofossil zonations with respect to these boundaries, since the GSSP "must be used without modification...[although an author may]...express his personal opinion, but the author will be obliged to make clear what is the general consensus compared to his personal views" (Remane *et al.*, 1995, p.6).

Figure 2 contains a summary of the proposals for Upper Cretaceous stage-boundary stratotypes and marker events put forward by the Brussels Working Groups. The formal proposals will be published by summer 1996 in the conference volume of the Brussels meeting. The candidates for event and stratotype had to fill certain requirements in order to qualify: the correlation potential of the GSSP had to be demonstrated; the event and stratotype had to respect historical precedents where possible; the boundary event had to lie within a "bundle of successive events" (Remane *et al.*, 1995, p.5); the boundary sections had to be well-exposed, easily accessible, unaltered, complete, expanded, with one facies crossing the boundary, and not tectonically disturbed; they had to contain a variety of well-preserved fossil groups, which showed no ecologically-related FADs or LADs across the boundary; the boundary event had to preferably be a FAD; data concerning magnetostratigraphy, chemostratigraphy and radiometric dates were expected to be available also. Despite the requirements, it was realistically observed that 'the perfect stratotype' was unlikely to exist for every boundary, and that it may not have been possible to fulfill every criterion.

Figure 3 summarises the nannofossil data in relation to the proposed boundaries, using the Sissingh/Perch-Nielsen scheme as a framework but incorporating the author's original work, and thus introducing some novel events (the utility of these and a number of other events is currently being assessed further before a new zonation scheme is published). Gaps in the data are currently being filled, and all of the nannofossil data is being prepared for publication.

The nannofossil data and confirmatory observations come from numerous sections, including: Belgium, Bulgaria, the Czech Republic, Denmark, England, France, Germany, The Netherlands, the North Sea, Poland, Russia, South Africa, Spain, the USA (Arizona, Colorado, Texas, the eastern sea-board), and the Indian, North and South Atlantic, and Pacific Oceans.

Nannofossil taxon names referred to herein are those in current usage and authors can be found in Perch-Nielsen (1985).

FIGURE 3: POTENTIALLY USEFUL NANNOFOSSIL EVENTS AROUND UPPER CRETACEOUS (SUB-)STAGE BOUNDARIES - STATE OF THE ART

*BASED ON STAGE -BOUNDARY WORKING GROUP PROPOSALS, BRUSSELS, 1995

STAGE*	SUBSTAGE*	NF EVENTS	NF ZONE	STAGE*	SUBSTAGE*	NF EVENTS	NF ZONE	STAGE*	SUBSTAGE*	NF EVENTS	NF ZONE
TURONIAN	UPPER	LAD <i>R. planus</i>	CC13B	SANTONIAN	UPPER	FAD regular <i>C. obscurus</i>	CC17	MAASTRICHTIAN	UPPER	FAD <i>M. prinsii</i>	CC26B
		FAD <i>L. septenarius</i>				FAD <i>A. regularis</i>				FAD <i>C. kamptneri</i>	CC26A
		FAD <i>Z. biperforatus</i>	CC13A			FAD <i>A. minimus</i>				FAD <i>N. frequens</i> †	CC25C
		FAD <i>Marthasterites</i>								FAD <i>M. murus</i>	CC25B
	MIDDLE	no decision	CC12		MIDDLE	?FAD <i>U. socialis</i>	CC16		UPPER	LAD <i>A. octoradiata</i>	CC25B
		FAD <i>L. maleformis</i>				?FAD <i>L. cayeuxii</i>				?FAD <i>L. quadratus</i>	
		FAD <i>Z. kerguelensis</i>				no decision				?LAD <i>C. obscurus</i>	
		FAD <i>E. eximius</i>									CC25A
	LOWER	FAD <i>K. magnificus</i>			LOWER				LOWER	no decision	
		FAD <i>C. woolgarii</i>								?LAD <i>R. levis</i>	CC24
		FAD <i>A. octoradiata</i> , <i>H. anceps</i>								LAD <i>B. magnum</i>	
		LAD <i>S. achylosus</i>								LAD <i>T. orionatus</i> , <i>U. trifidus</i>	CC23B
CENOMANIAN	UPPER	FAD <i>W. devonense</i>		CONIACIAN	UPPER	LAD <i>L. septenarius</i>	CC15	CAMPANIAN	UPPER	LAD <i>B. parca constricta</i> , <i>B. coronum</i>	
		FAD <i>Q. gartneri</i>				FAD <i>C. undulatopectatus</i>				LAD <i>A. minimus</i> , <i>A. scotus</i>	CC23A
		LAD <i>M. chistiatus</i>	CC10B			LAD <i>F. oblongus</i>				FAD <i>P. neubergicus</i>	
		LAD <i>Cret. striatus</i>				LAD <i>Q. gartneri</i>				LAD <i>H. bugensis</i>	
	MIDDLE	LAD <i>A. albianus</i>			MIDDLE	FAD <i>L. grillii</i>			UPPER	LAD <i>E. eximius</i>	
		FAD <i>T. minimus</i>				FAD <i>R. anthophorus</i>				LAD <i>R. anthophorus</i>	
		no decision				?FAD <i>P. fibuliformis</i>				LAD <i>B. dissimilis</i>	CC22C
						FAD <i>I. (M.) subquadratus</i>	CC14			LAD <i>H. circumradiatus</i>	
	LOWER	LAD <i>C. kennedyi</i> , <i>G. nanum</i> , <i>L. glans</i>	CC10A		LOWER				UPPER	LAD <i>G. coronadventis</i> , <i>Z. biperforatus</i>	
		FAD <i>C. biarcus</i>								FAD <i>R. levis</i>	
										FAD <i>L. praequadratus</i>	
										no decision	CC22B
ALBIAN	UPPER (pars.)	FAD <i>C. inermis</i>		CAMPANIAN	UPPER	FAD <i>V. koeneni</i>		CAMPANIAN	UPPER	?LAD <i>B. parca parca</i>	
		FAD <i>L. acutus</i>				?FAD <i>M. stauraphora</i>				?LAD <i>L. grillii</i>	
		FAD <i>H. trabeculatus</i>								BOREAL	
		LAD <i>W. britannica</i> , <i>B. africana</i>	CC9C							FAD <i>H. bugensis</i>	
	LOWER	FAD <i>C. kennedyi</i>			LOWER				UPPER	FAD <i>U. trifidus</i>	
		FAD <i>P. cretacea s.s.</i> , <i>G. praeobliquum</i>								FAD <i>U. sissinghii</i>	
		FAD <i>R. planus</i>								FAD <i>C. aculeus</i>	
		FAD <i>G. theta</i>									
	LOWER	LAD <i>S. glabra</i>			LOWER	LAD <i>C. coronatus</i> , ? <i>H. turonicus</i>	CC13B		UPPER	FAD <i>N. cohenii</i>	
										FAD <i>B. parca constricta</i> , <i>C. verbeekii</i>	
										FAD <i>B. parca parca</i>	
										?FAD <i>B. magnum</i>	
ALBIAN	UPPER (pars.)	FAD <i>R. globotruncanoides</i>	CC9B	CAMPANIAN	UPPER	FAD <i>C. rotundatus</i>		CAMPANIAN	UPPER	?FAD <i>O. campanensis</i>	CC17
		FAD <i>C. anfractus</i>								LAD <i>M. testudinarius</i>	
		LAD <i>Arkhangelskiella</i> ? sp.									
		FAD <i>G. chiasta</i> , <i>C. anglicum</i>									
	LOWER	FAD <i>Arkhangelskiella</i> ? sp.			LOWER				UPPER		
		LAD <i>H. albionis</i>									
		FAD <i>F. turnseiffelii</i>	CC9A								

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