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A Lower Cretaceous nannofossil zonation for the North Sea Basin

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ABSTRACT – Analysis of cored sections from the Central North Sea Basin, boreholes from the onshore Netherlands and onshore sections from the UK and Germany has enabled a major reappraisal of Lower Cretaceous nannofossil datums. The Lower Albian to Upper Barremian interval has, in particular, been comprehensively amended. Five new species, *Crucibiscutum bosunensis* sp. nov., *Crucibiscutum ryazanicum* sp. nov., *Lithraphidites houghtonii* sp. nov., *Seribiscutum dentatum* sp. nov., *Staurolithites palmula* sp. nov. and one new sub-species, *Biscutum constans cavum* ssp. nov. are described. *J. Micropalaeontol.* **20**(1): 45–80, July 2001.

INTRODUCTION

This paper has its foundations in calibration work carried out on some of the most important Lower Cretaceous reservoir sections in the North Sea Basin, namely the Aptian–Albian successions of the Britannia, Captain, Blake and Goldeneye fields. A detailed calibration was essential if basin-wide facies maps, sequence and seismo-stratigraphic markers were to be interpreted consistently around the basin (Jeremiah, 2000). Inherent weaknesses were identified at an early stage between the accepted lowermost Albian through Upper Barremian calibration of palynological and nannofossil events (e.g. nannofossil data often suggested a much higher top Lower Aptian than palynological data). The discrepancies were explained by the lack of extensive Lower Albian to uppermost Barremian nannofossil studies that had been calibrated to ammonite-dated material. Palynological datums from an ammonite calibration perspective were at a more advanced stage (Duxbury, 1983; Heilmann-Clausen & Thomson, 1995).

The most recent Boreal zonation of Bown *et al.* (1998) was a compilation of previous works, mainly by Jakubowski (1987), Crux (1989, 1991) and Jeremiah (1996) with additional Ryazanian to Lower Barremian resolution provided from the unpublished PhD thesis of Rutledge and offshore data of Gallagher. The Upper Barremian to Lower Albian interval, however, remained poorly calibrated. A field-scale subdivision of the Late Barremian to Early Aptian (BC16 through BC20) of the Britannia Field by Gallagher in Bown *et al.* (1998), although documenting many of the important datums, only resulted in highlighting the poor macrofossil control available at this time. This paper attempts to re-address this primary weakness in the Boreal nannofossil zonation. Calibration to both palynological and macrofossil data has allowed this section to be re-evaluated.

A number of important onshore UK sections are first described, including the Lower Aptian strata from the Speeton section (Mitchell & Underwood, 1999), the overlying Albian to Lower Cenomanian Red Chalk section at Speeton (Mitchell, 1995) and Upper Barremian-dated Speeton Clay from the BGS West-Heslerton II borehole. Supplementary UK nannofossil data are provided from the Lower Aptian Atherfield Clay in the RC1544 borehole, a sequence which is poorly calcareous at outcrop on the Isle of Wight (Bischoff & Mutterlose, 1998). The Aptian nannofossil zonation is further constrained by various ammonite-dated sections from the Saxony Basin (Netherlands and Germany) and an isolated oucrop from the UK (Baulking Quarry). Nannofossil data from German sections are described in the Appendices. A brief review of the main sections studied is followed by a detailed breakdown of the new ammonite zonation. The differences between the interpreted ranges and utilization of alternative markers has made it more practical to establish another zonation rather than simply amend the BC Zonation of Bown *et al.* (1998). The zones are numbered downwards, a reference to this zonation having primarily been constructed for offshore studies. The zonation makes particular use of quantitative events. With more sections, both onshore and offshore having been studied, it is apparent that many previous zonal markers (e.g. *Prediscosphaera columnata, Farhania varolii, Diazomatolithus lehmanii*) have sporadic occurrences outside published ranges. The nannofossil distribution charts are biased towards the Aptian to Upper Barremian intervals, the stratigraphical interval that is most important from a North Sea, Lower Cretaceous reservoir perspective.

METHODS

Sample preparation

For light microscope examination, the samples were prepared by placing a small amount of sediment directly onto a microscope slide. A pipette was used to place a drop of distilled water onto the sample and smeared out into a thin layer by using a clean picking brush (size 101). The smeared sample was dried on a hot plate and a coverslip was attached using a permanent-mounting medium (Norland Optical Adhesive or Canada balsam). The picking brush is placed in 10% HCl to remove any remaining residue.

Counting technique

Samples were examined with a light microscope at a magnification of 1000 ×. A transect of thirty fields of view is taken with all specimens counted. Some species (e.g. *Watznaueria barnesae*) are so profuse that only ten or, in some instances, five fields of view are counted. Its abundance is subsequently multiplied out to thirty fields of view.

The following relative abundance categories which are used extensively in industry are also utilized in the present study:

rare: less than 1 specimen per 30 fields of view but present on scanning.

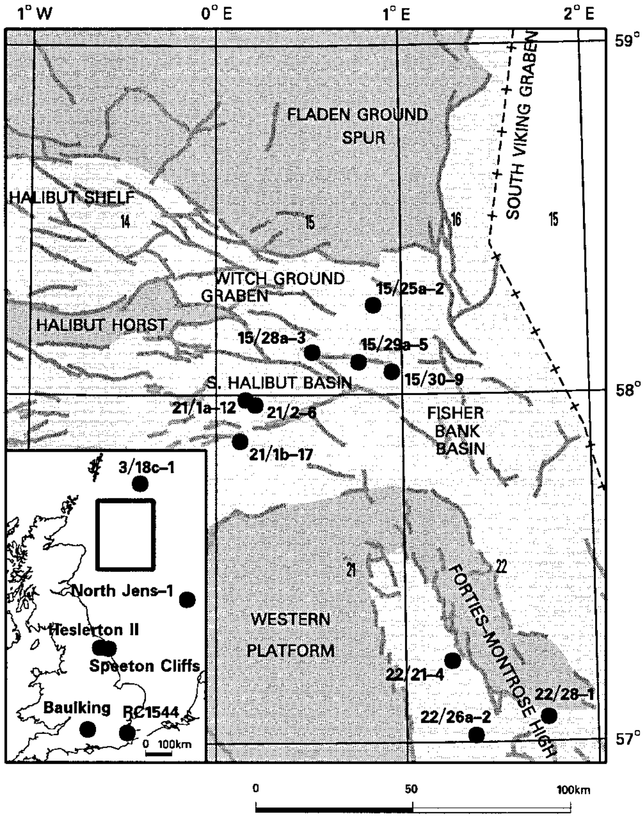


Fig. 1. Location map of sections analysed from North Sea Basin and onshore UK. Note the light shaded area in the large-scale UK map indicates the major Jurassic depocentres and criteria for differentiation of the various sub-basins utilized in the UK North Sea.

occasional: 1–2 specimens per 30 fields of view.
common: 3–10 specimens per 30 fields of view.
abundant: 11–30 specimens per 30 fields of view.
influx: individuals are a major component of assemblage – greater than 1 specimen per field of view.

The distribution charts abundance counts are based upon a transect of 30 fields of view. P refers to present outside this initial count while R refers to reworked. The main markers on each distribution chart are highlighted with an asterisk.

MATERIAL STUDIED

The stratigraphic results presented here are based on data from several localities in England, the Netherlands and Germany, together with released data from numerous North Sea exploration wells. The locations of field samples studied from mainland UK and North Sea wells are indicated on Figure 1. Precise locations of UK outcrop localities are cited below, relative to the UK national grid. The German outcrop sections and Netherlands onshore wells are referenced in the Appendices. Co-ordinates are also given for all Netherlands onshore boreholes discussed in the text. A chronostratigraphic synopsis of the studied localities is given in Figure 2.

Well and outcrop listing

- **North Sea Basin (11):** 3/18c-1, 15/25a-2, 15/28a-3, 15/29a-5, 15/30-9, 21/1b-17, 22/21-4, 22/26a-2, 22/28a-1, Danish North Jens-1, Norway 31/3-3. These data are complemented by nannofossil data from 17 cored wells and 13 non-cored sections from throughout the UK North Sea Basin (Jeremiah, 2000).
- **Netherlands onshore boreholes (6):** Spijkenisse-1, Sleen Dommerskanaal-1, Wijk-5, Beilen-2, Tubbergen-6 and Westerbork-1.
- **UK onshore sections and boreholes (5):** Speeton Cliffs, Heslerton II borehole, RC1544 borehole, Baulking Quarry, Isle of Wight.
- **German onshore sections and boreholes (7):** Suddendorf, Vohrum, Sarstedt, Rothenberg, Gehrdener-Berg, Alstatte and Kirchrode II borehole.

The main UK onshore sections studied are discussed briefly in the following sections. Nannofossils recovered in these sections are presented in range charts (Figs 3–5) or in the Appendices.

1. Yorkshire – Speeton Cliffs (Red Chalk and Speeton Clay)
2. Yorkshire – Heslerton Borehole II (Speeton Clay)
3. Kent – Borehole RC1544 (Atherfield Clay/Hythe Beds)

Speeton (Red Chalk) [TA 155 755]. The Red Chalk at Speeton (Fig. 3) is divided into five lithostratigraphic members (Mitchell, 1995). The ammonite zonation, by inferrence, is based upon regionally correlatable bivalve and belemnite events. Ammonites are extremely scarce having only been recorded from the lower part of the Speeton Beck and Queen Rocks Member (Mitchell, 1995). The Albian to Cenomanian boundary at Speeton can be accurately placed by using a distinctive stable carbon isotope ($\delta^{13}C$) excursion which is also recognized at the expanded Albian to Cenomanian succession in the Vocontian Trough (Gale *et al.*, 1996). Samples supplied by S. F. Mitchell and C. Underwood from the specific numbered beds of Mitchell (1995) were analysed for nannofossils. The results support much of the log correlation and regional unconformities presented in Mitchell (1995).

The main surfaces recorded are as follows.

1. The flooding surface that corresponds to the transition from the Speeton Clay into the Red Chalk lies close to the *spathi-intermedius* Subzonal boundary. Ammonites recovered from the top of the Speeton A Beds were identified as *Hoplites spathi* and *Hamites* spp. (Owen pers. comm., 1997). Belemnite evidence suggests an *intermedius* Subzone for the basal Red Chalk Queen Rocks Member at Speeton (Mitchell, 1995). This flooding surface also corresponds to the flooding of the Carstone over much of Norfolk, Lincolnshire and Humberside. Gault Clay sedimentation over much of southern Britain was established during this period.
2. The regional *cristatum* erosive event (Owen, 1972, 1975) is recorded at Speeton and lies at the Queen Rocks Bed 2–Bed 3 boundary. Uppermost Middle Albian sediments are absent.
3. The Breccia Nodule Bed of Jeans (1973, 1980) marks a regionally correlatable intra-*auritus* Subzonal hiatus at the base of the Dulcey Dock Member, Bed 5 (DD5). This hiatus is recorded at South Ferriby (Gaunt *et al.*, 1992; Mitchell, 1995; Jeremiah, 1996), the Cambridgeshire Gault Clay (Mitchell, 1995; Jeremiah, 1996) and at the type Gault Clay

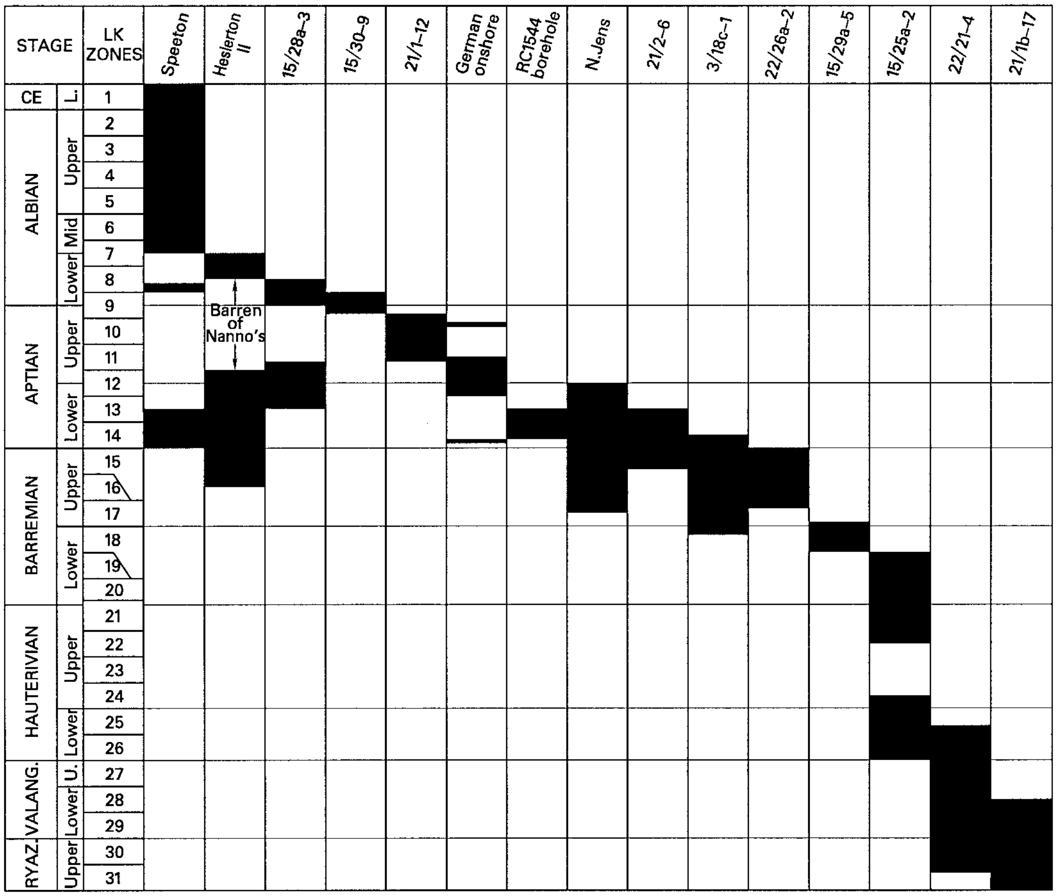


Fig. 2. Stratigraphic sections studied. Note the emphasis is on lowermost Albian to Upper Barremian sections. This stratigraphic interval was poorly calibrated to macrofossil stratigraphy in previous schemes.

succession at Folkestone (Jeremiah, 1996). At Folkestone the equivalent unconformity lies at the base of the Greensand Seam (Bed XII of Jukes-Browne & Hill, 1900).

4. The presence of the Albian–Cenomanian boundary within the Weather Castle Member, Bed 7, is confirmed with nannofossil data.

Speeton (Speeton A & B Beds). Samples collected by S. F. Mitchell and C. Underwood from the re-defined Speeton UB and LA Beds (Mitchell & Underwood, 1999) were analysed for their calcareous nannofossil content (Fig. 4). Prolific ammonite data resulted in an accurate calibration of this Lower Aptian sequence. Uppermost Barremian *bidentatum* ammonite-bearing UB3 black claystones from immediately below the UB2 beds were also analysed (samples provided by P. Rawson). The dark grey marls and black mudstones of the Speeton UB2 and UB1 beds correlate directly with the Fischshiefer or Valhall V5 Beds (Johnson & Lott, 1993) of the North Sea Basin, based on nannofossil data. Organic mudstones typical of the Fischschiefer are mostly absent from the Speeton section. This lateral facies change is also present in the West Netherlands Basin, onshore Netherlands, where *Prodeshayesites*-bearing mudstones also appear to lack any major organic mudstone intervals. The basal condensed LA6 bed, based on nannofossil data, correlates with the Valhall V6 (Ewaldi Marl) – Valhall V5 boundary in the North Sea Basin. The pale marl deposits of the LA5 Beds, based on nannofossil data, can be directly correlated to the Valhall V6 Beds or Ewaldi Marl (Johnson & Lott, 1993) of the North Sea Basin. The remaining Aptian sequence has yet to be recovered from the Speeton Cliffs, a result of the mud-slides which characterize this part of the exposure.

A possible indication of the post-Ewaldi Marl (LA5 beds) succession can be gauged from the West Heslerton II borehole. Lower Cretaceous syndepositional faulting (Kirby & Swallow, 1987) may, however, have led to a considerable difference in these two successions.

West Heslerton borehole II (Speeton A & B Beds) [SE 9199 7589]. This borehole, drilled by the British Geological Survey in 1991, covers a section from the Upper Albian Red Chalk down into the Upper Barremian B Beds (Appendix C). This stratigraphic interval, until recently, was poorly understood from the stratotype succession of the Speeton Clay at the Speeton Cliffs. Mitchell & Underwood (1999) have recently documented the Lower Albian and Lower Aptian sequences from Speeton, but Upper Aptian and Upper Barremian successions have yet to be described as a result of non-exposure due to faulting and slumping.

Investigation of the West Heslerton II borehole has increased our understanding of the Lower Albian/Upper Barremian

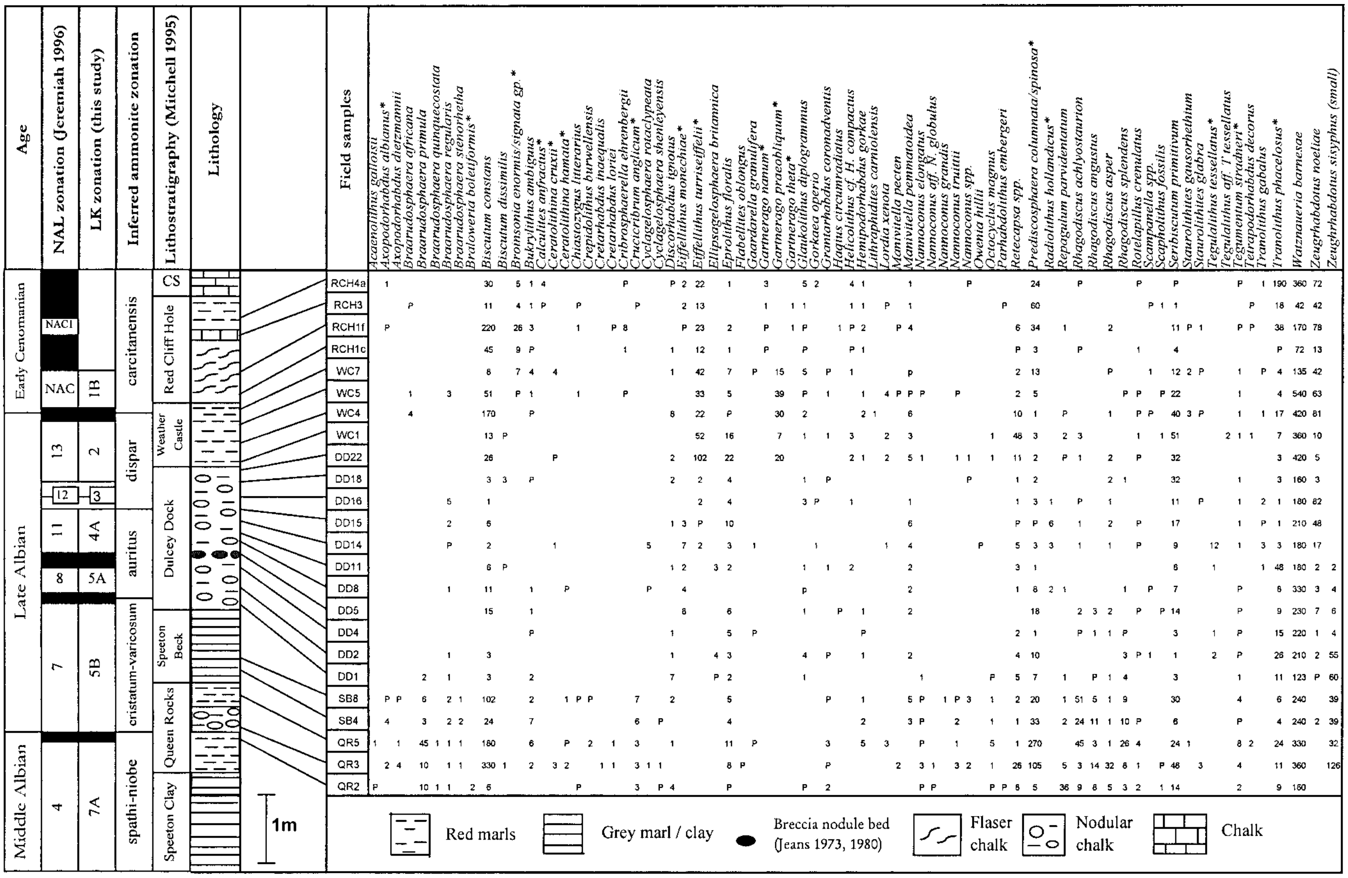


Fig. 3. Stratigraphical distribution of nannofossils from Speeton Cliffs (Red Chalk), Yorkshire. Field sample numbering scheme refers to the bed nomenclature of Mitchell (1995). CS refers to the Crowe's Shoot Member. Note the regional *cristatum* erosive event (Owen, 1972, 1975) at the base of Bed QR3, the intra-*auritus* hiatus at the Breccia Nodule Bed and the first indications of Zone LK1 within the early Cenomanian part of the upper Weather Castle Member.

sequence of the Speeton area. It should be emphasized, however, that variations in thickness and sedimentary expressions vary markedly north of the Howardian–Flamborough Fault Zone (Kirby & Swallow, 1987). This can be proven by the markedly different field descriptions of temporary exposures at West Heslerton village by Ennis (1932) [SE 914 756] and Kaye (1964) [SE 914 756].

LCE Borehole RC1544 (Atherfield Clay/Hythe Beds) [142150N603315E/1:2500 Ordnance Survey]. This core penetrates a succession across the lower Hythe Beds (*deshayesi* Zone) to Atherfield Clay (*forbesi* Zone) boundary (Fig. 5). The Atherfield Clay succession penetrated is dominated by calcareous siltstones and dark grey mudstones that represent the initial Lower Aptian marine transgression over the non-marine Wealden Group (Ruffell & Wach, 1991). The Atherfield Clay on the Isle of Wight is wholly of *forbesi* age, the underlying Perna Bed being equivalent to the upper part of the *fissicostatus* Zone. Further north in Kent, however, the Perna Bed is absent and it is considered possible that the Atherfield Clay extends into the *fissicostatus* Zone in this region. The Atherfield Clay is proven to correlate with the Fischschiefer (Valhall V5 Beds) of the North Sea Basin (Johnson & Lott, 1993) by the presence of *Nannoconus pseudoseptentrionalis* and the *Cyclagelosphaera margerelii* acme. At Speeton, equivalent *forbesi* ammonite-dated sediments have mostly been removed at the Speeton U1B/LA6 hiatus (Mitchell & Underwood, 1999).

The lower Hythe Beds in the RC1544 borehole are correlatable with the Ewaldi Marl (Valhall V6 Beds) of the North Sea and the Speeton upper LA5 Beds described by Mitchell & Underwood (1999) based on the presence of *Eprolithus floralis* below the FAD of *Farhania varolii*. At RC1544 the lower Hythe Beds are dominated by glauconitic clays, cemented limestones and calcareous sandstones, the so called 'Rag and Hassock' (Ruffell, 1992).

ZONATION

The zonation outlined below was developed as a practical tool for subdividing the uppermost Ryazanian to lowermost Cenomanian of onshore sections (mainly from England and Germany), borehole material from the Netherlands and offshore material from throughout the Central North Sea Basin (Fig. 1). Work was started, with the aim of improving the calibration of the Lower Albian to Upper Barremian BC scheme of Bown *et al.* (1998) and constructing a scheme useful for both academic and industrial purposes. In this study, 31 zones are defined for the uppermost Ryazanian to lowermost Cenomanian interval.

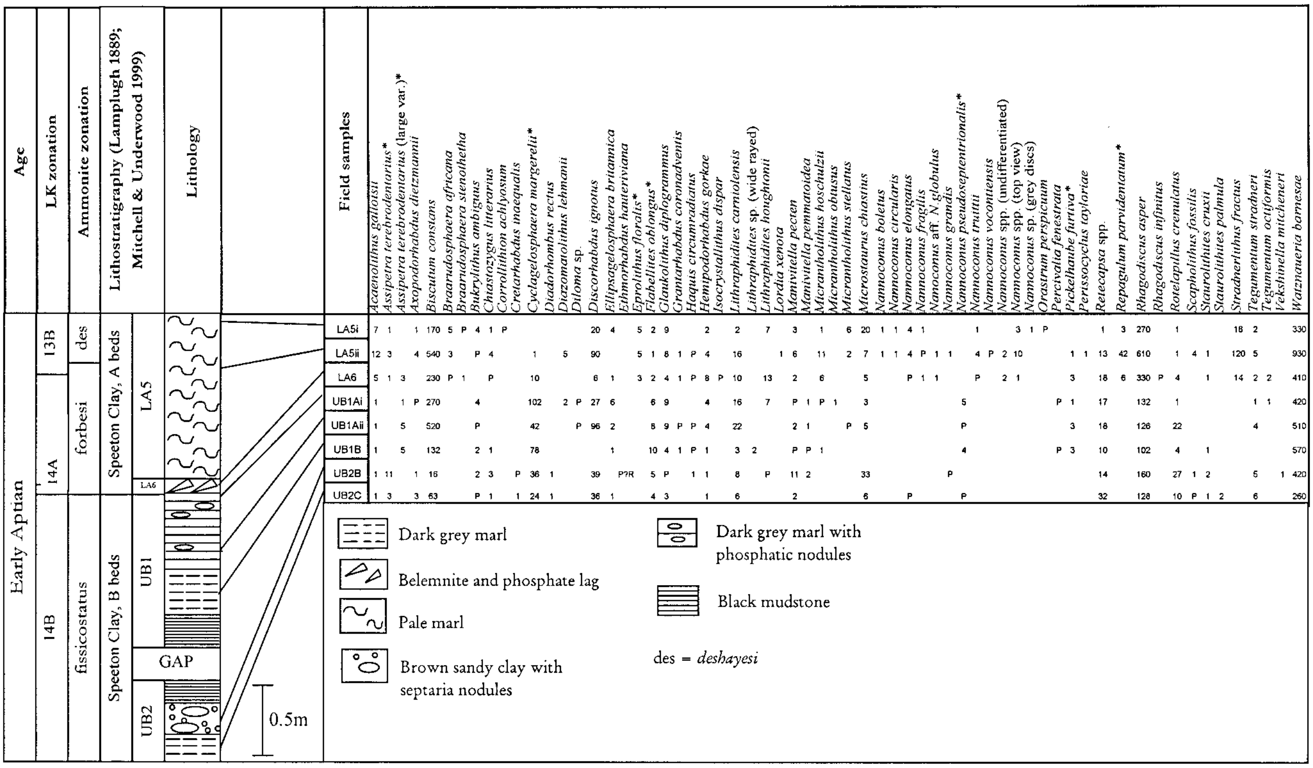


Fig. 4. Stratigraphical distribution of nannofossils from Speeton Cliffs (upper B/lower A Beds), Yorkshire. Note the absence of LK14B *forbesi*-dated sediments as a result of an intra-*forbesi* hiatus at Speeton (Bed LA6/Bed UB1 boundary).

Nine zones are defined for the first time (LK10, LK11, LK13, LK14, LK15, LK17, LK20, LK24 and LK31) and three zones are based on alternative zonal markers for the first time (LK12, LK25 and LK30). This study has also changed the stratigraphic significance of many established zonal markers. They are correlated with the macrofossil (MF) zones and compared with the previous BC zonation of Bown *et al.* (1998) in Figures 6 and 7. Composite range charts of biostratigraphically useful species are presented in Figures 8 and 9. FDO refers to first downhole occurrence, whilst LDO indicates the last downhole occurrence; the FAD being the first appearance datum or evolutionary appearance and LAD, the last appearance datum or extinction event.

Broinsonia enormis Zone – LK1

Top: LAD of *Gartnerago praeobliquum* [Jakubowski, 1986].
Base: FAD of occasional/abundant *Broinsonia enormis/dentata* group, *Gartnerago theta*, *G. nanum* and *G. chiasta* [Jeremiah, 1996].
Age: earliest Cenomanian (lowermost *mantelli* MF Zone, lower *carcitanense* Subzone), locally may range into the uppermost *dispar* MF Zone, uppermost *perinflatum* MF Subzone).

LK1 can be subdivided into two subzones.

Subzone LK1A

Top: LAD of *Gartnerago praeobliquum* [Jakubowski, 1986].
Base: FAD of *Calculites anfractus* [Jeremiah, 1996].
Age: earliest Cenomanian (lowermost *mantelli* MF Zone, lower *carcitanense* Subzone).

Remarks: *Calculites anfractus* has a well-defined FAD from UK onshore sections within the earliest Cenomanian; e.g. Arlesey, Eastbourne, South Ferriby (Jeremiah, 1996) and Speeton (Fig. 3). At Copt Point, Folkestone [TR 2414 3645], *C. anfractus* appears within the earliest Cenomanian, 2 m above the base of the Glauconitic Marl. An earlier FAD for *Calculites anfractus* was reported from the Boreal Late Albian by Bown *et al.* (1998) and Burnett (1998). The earlier FAD for *C. anfractus* in these studies was probably based on a solitary record 10 m below the base Cenomanian at the Tethyan Mt Risou section in southern France (Gale *et al.*, 1996). This isolated occurrence would indicate an earlier FAD in southern France than in England for a nannofossil that exhibits marked Boreal provincialism. Jeremiah (1996), by contrast, analysed the same suite of samples as Gale *et al.* (1996) but identified the FAD and subsequent sporadic occurrences of *C. anfactus* 40 m above the Albian/Cenomanian boundary at Mt Risou.

Subzone LK1B

Top: FAD of *Calculites anfractus* [Jeremiah, 1996].
Base: FAD of occasional/abundant *Broinsonia enormis/dentata* group, *Gartnerago theta*, *G. nanum* and *G. chiasta* [Jeremiah, 1996].
Age: earliest Cenomanian (earliest *mantelli* MF Zone, early *carcitanense* Subzone), locally may range into the latest *dispar* MF Zone, latest *perinflatum* MF Subzone).
Note: the latest Albian *Arrhaphoceras briacensis* ammonite Subzone (Gale *et al.*, 1996) is not utilized in this study since it it has

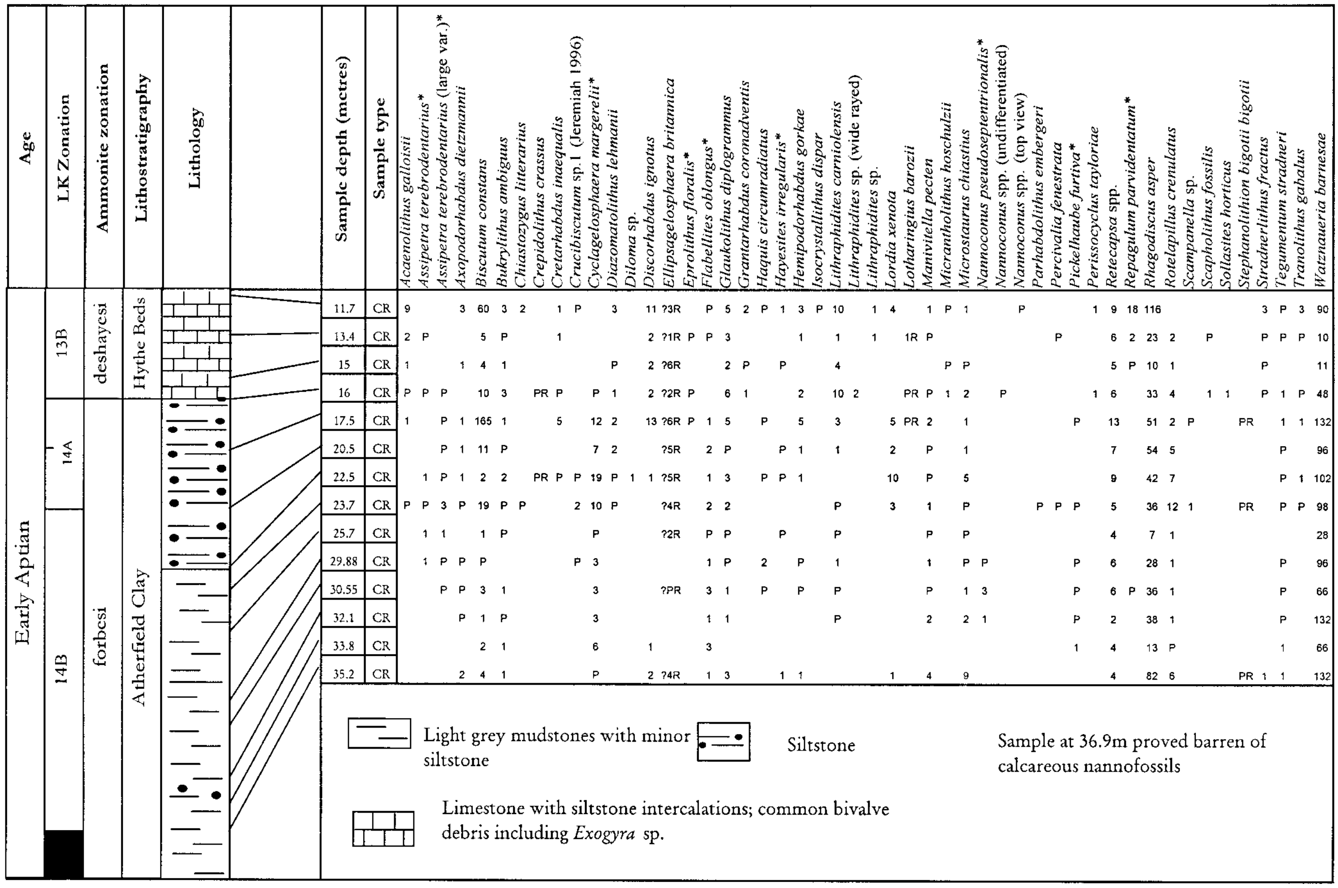


Fig. 5. Stratigraphical distribution of nannofossils from London Continental Engineering borehole RC1544, Ashford, Kent. Note the late Jurassic reworking including common *Ellipsagelosphaera britannica*. This section exhibits a more pronounced Tethyan influence than sections from the North Sea Basin. Note the consistent occurrences of *Diazomatolithus lehmanii* and *Hayesites irregularis*.

only been recognized, to date, in the southern European Tethyan Realm.

Remarks: the FAD of *Gartnerago theta*, *G. nanum* and *G. chiasta* associated with the increase in the *Broinsonia enormis/dentata* group coincides with the Albian–Cenomanian boundary in southern England; e.g. Arlesey, Folkestone (Jeremiah, 1996). In these exposures, however, the top Albian beds are truncated.

In the Red Chalk facies at Speeton (Fig. 3) the Albian–Cenomanian boundary can be accurately placed by using a distinctive stable carbon isotope ($\delta^{13}C$) excursion (Mitchell, 1995) which is also recognized at the expanded Albian–Cenomanian boundary successions documented from the Vocontian Trough, southern France (Gale *et al.*, 1996). At Speeton, however, as in southern England localities, LK1 nannofossil assemblages remain restricted to the earliest Cenomanian. Currently, only at the Mt Risou section in southern France have LK1 assemblages been recorded from definitive uppermost Albian sediments (Gale *et al.*, 1996; Jeremiah, 1996). In the Dutch Sector of the southern North Sea Basin and West of Shetland Basin similar expanded uppermost Albian sections (greater than 100 m) as that developed at Mt Risou exist. It is from these areas that latest Albian LK1 assemblages, macrofossil recovery allowing, may be described from the Boreal Realm. The risks of provincialism and diachroneity remain, however, between the Boreal and Tethyan realms and, until otherwise proven, LK1 assemblages remain indicative of the earliest Cenomanian in the Boreal area.

Gartnerago chiasta and *Crucibiscutum hayi* are widespread within LK1 of southern Britain (e.g. Arlesey, Folkestone, Eastbourne and the Dutch Sector of the southern North Sea (Jeremiah, 1996) but are rarely recorded further north in the Red Chalk facies of Yorkshire (e.g. South Ferriby; Jeremiah, 1996, Speeton, Fig. 3) and the Central North Sea Basin.

Eiffellithus turriseiffelii Zone – LK2

Top: FAD of occasional/abundant *Broinsonia enormis/dentata* group, *Gartnerago theta*, *G. nanum* and *G. chiasta* [Jeremiah, 1996].

Base: LAD of *Radiolithus hollandicus* [Jeremiah, 1996].

Age: Late Albian (*dispar* MF Zone).

Remarks: the LAD of occasional/abundant *Gartnerago praeobliquum* (NLK3B of Jakubowski, 1987) is an approximate marker for the top of LK2 in the North Sea Basin. In southern Britain and Yorkshire sporadic incursions of common *G. praeobliquum* range into the basal Cenomanian, Zone LK1: e.g. Arlesey (Jeremiah, 1996) and Speeton (Fig. 3).

The LAD of *Hayesites albiensis* is recorded from the base of this zone in southern England (Folkestone Warren borehole,

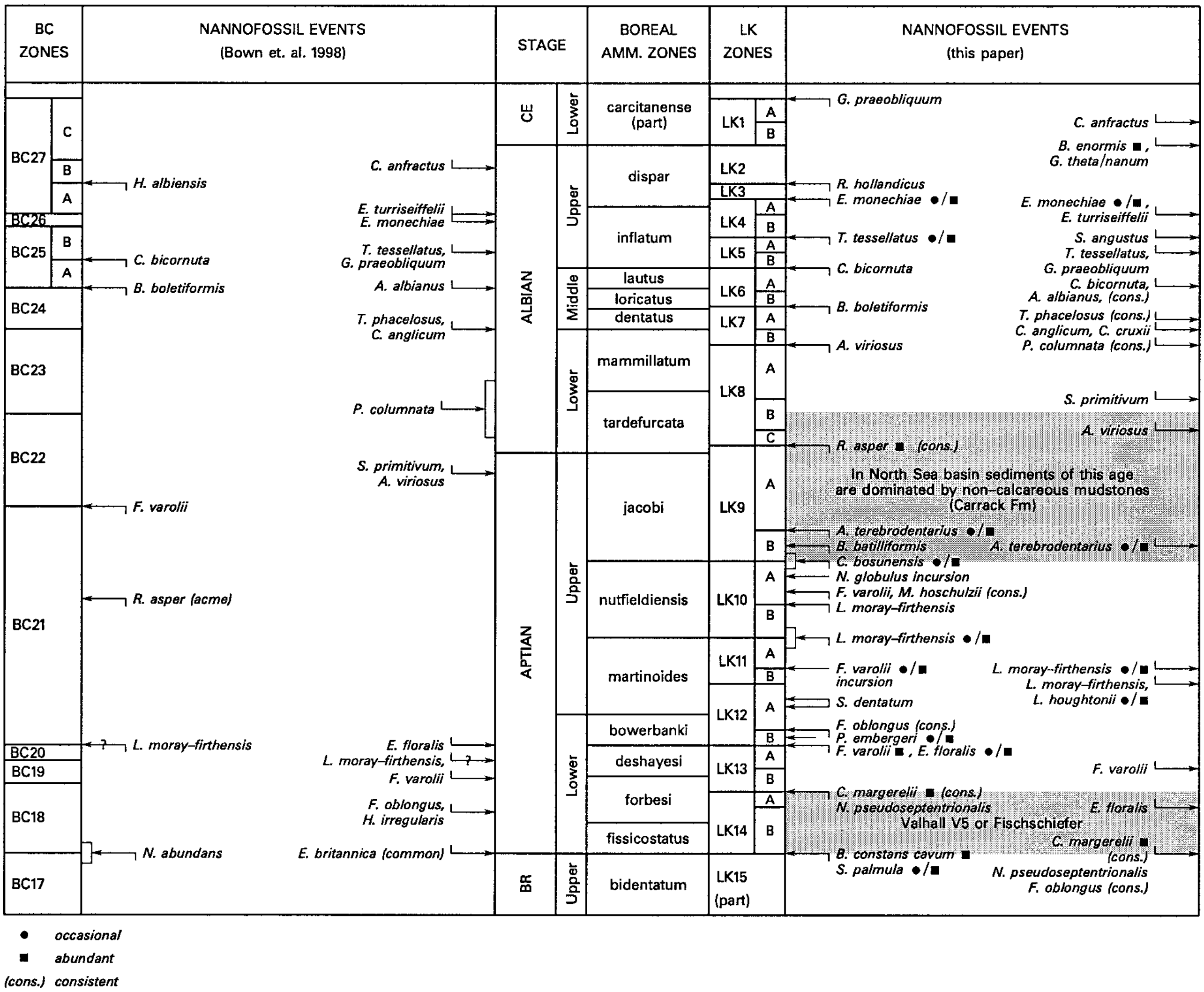


Fig. 6. Lowermost Cenomanian to uppermost Barremian nannofossil zonation scheme compared with Bown *et al.* (1998) scheme.

Jeremiah, 1996). This, though, is an extremely rare occurrence outside its normal UK stratigraphic range. It is more usual to find *H. albiensis* associated with *varicosum* Subzonal (intra *inflatum* Zone) to intra-*mammillatum* Zonal sediments (Chamberlain's Barn, Nine Acres Pit [Jeremiah, 1996] and Mundays Hill [Crux, 1991]). *Hayesites albiensis* appears to to be mostly restricted to southern England (exception being a single record from the West Heslerton II borehole; Jeremiah, 1996), a possible reflection of the Tethyan provincialism exhibited in this species.

Radiolithus hollandicus Zone – LK3

Top: LAD of *Radiolithus hollandicus* [Jeremiah, 1996].
Base: LAD of common *Eiffellithus monechiae* [this study].
Age: Late Albian (early *dispar* MF Zone, early *rostratum* MF Subzone).

Staurolithites angustus Zone – LK4

Top: LAD of common *Eiffellithus monechiae* [this study].
Base: LAD of common *Tegulalithus tessellatus* [this study] and FAD of *Staurolithites angustus* [Jeremiah, 1996].
Age: Late Albian (earliest *dispar* MF Zone, earliest *rostratum* MF Subzone/late *inflatum* MF Zone, late *auritus* Subzone).
Remarks: LK4 has been subdivided into two subzones.

Subzone LK4A

Top: LAD of common *Eiffellithus monechiae* [this study].
Base: FAD of common *Eiffellithus monechiae* [this study] and FAD of *Eiffellithus turriseiffelii* [Thierstein, 1976].
Age: Late Albian (earliest *dispar* MF Zone, earliest *rostratum* Subzone to late *inflatum* MF Zone, late *auritus* Subzone).
Remarks: the FAD of *E. turriseiffelii* has been used by many authors as an intra-Albian zonal marker (Thierstein, 1976; Sissingh, 1977 and, more recently, Bralower *et al.*, 1993 and Bown *et al.*, 1998). The FAD of *E. turriseiffelii* is, however, difficult to identify accurately due to the proliferation at this level of intermediates between *E. monechiae* and *E. turriseiffelii.* This is compounded by the extreme rarity of true *E. turriseiffelii*

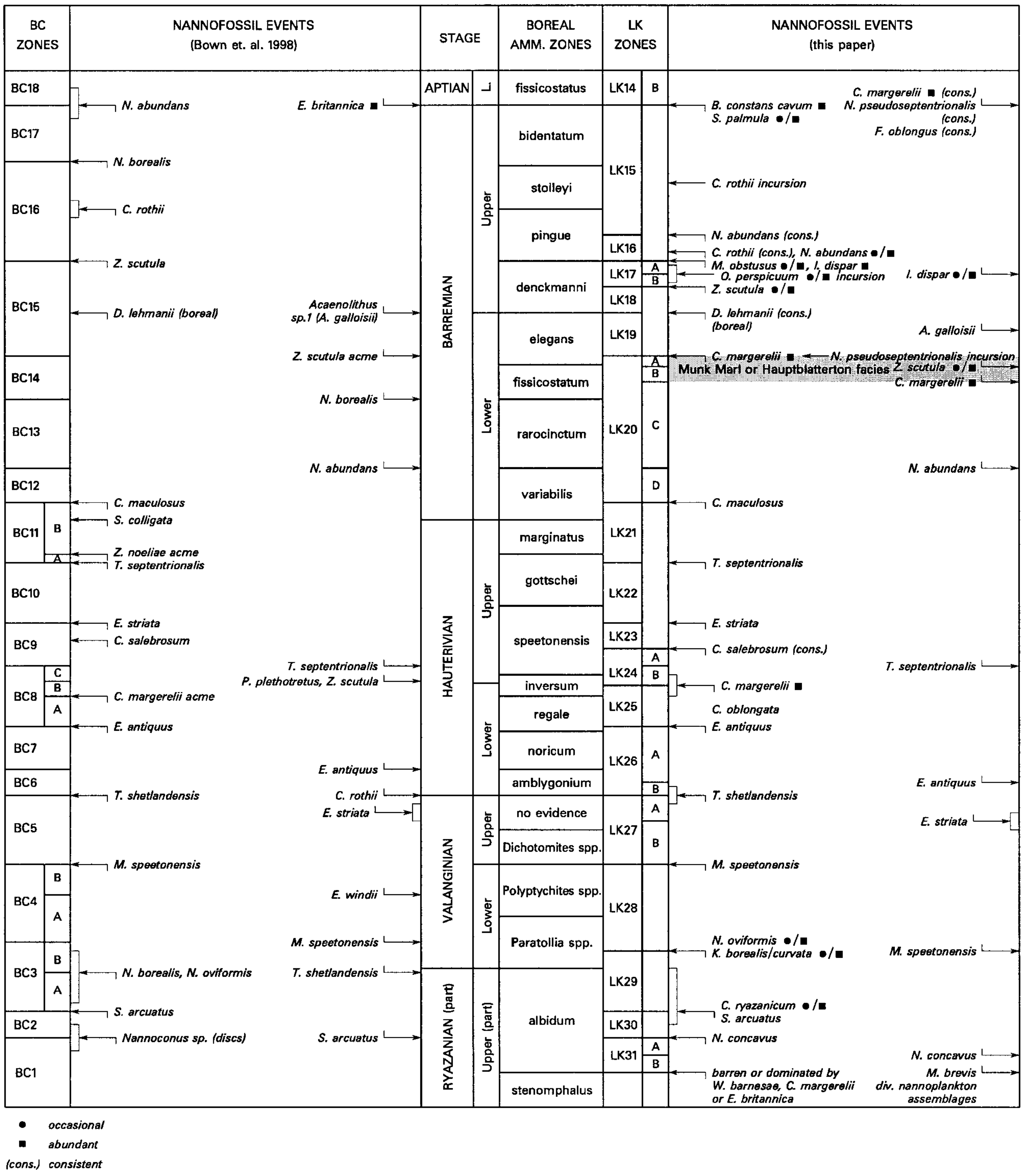


Fig. 7. Lowermost Aptian to uppermost Ryazanian nannofossil zonation scheme compared with Bown *et al.* (1998) scheme.

at the base of its range and the necessity for well-preserved and diverse assemblages. These criteria are rarely attained in the North Sea Basin assemblages (note the absence from Speeton samples DD5–DD11, Fig. 3). The abundance increase in *E. monechiae* is a far more easily recognizable datum.

The FAD of *E. turriseiffelii* has been adjusted to lie within the uppermost *auritus* MF Subzone. This amendment to the zonation of Jeremiah (1996) is a result of the incorrect assignment of *rostratum* MF sediments at the Burwell section (samples B12–B16 should belong to Bed 16 of Gallois & Morter, 1982).

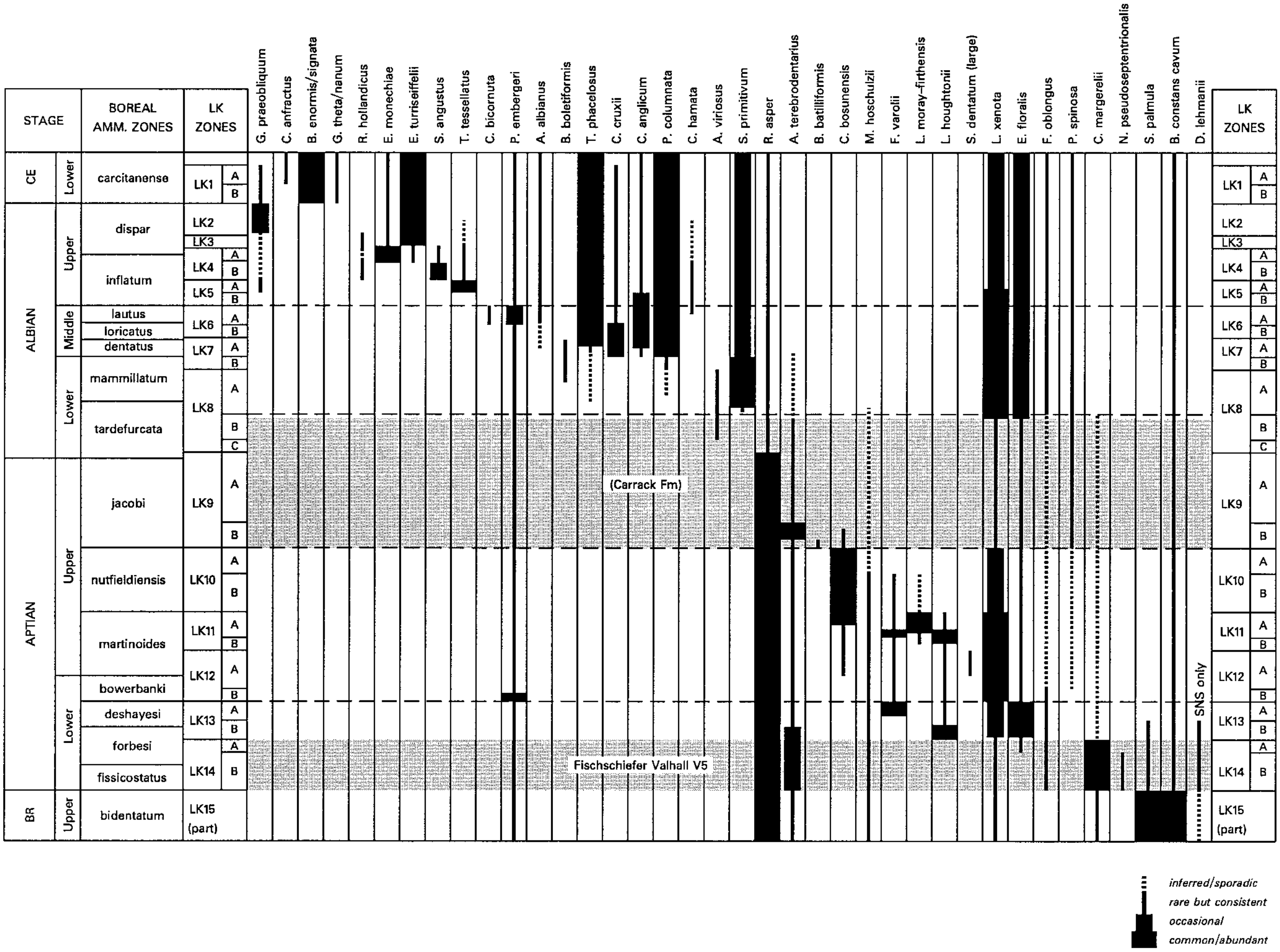


Fig. 8. Composite range chart of stratigraphically important lowermost Cenomanian to uppermost Barremian nannofossils of the North Sea Basin.

This refinement is confirmed by the presence of LK4A sediments of *auritus* age at Speeton (Fig. 3; samples DD14/DD15).

Subzone LK4B

Top: FAD of common *Eiffellithus monechiae* [this study] and FAD of *Eiffellithus turriseiffelii* [Thierstein, 1976].
Base: LAD of common *Tegulalithus tessellatus* [this study] and FAD of *Staurolithites angustus* [Jeremiah, 1996].
Age: Late Albian (late *inflatum* MF Zone, late *auritus* MF Subzone).
Remarks: *Staurolithites angustus* is restricted to LK4B in the North Sea Basin. Onshore, in southern Britain, *S. angustus* ranges into LK4A (NAL11 of Jeremiah, 1996). This species rapidly evolved into *Staurolithites rotatus* at the base of LK3 (Jeremiah, 1996). Anomalous records cited for *S. angustus* from the latest Albian to Cenomanian (Burnett, 1998) are probably due to the assignment of a plethora of smaller *Staurolithites* spp. to *S. angustus*.

A regional uppermost *auritus* unconformity is recorded from onshore UK (e.g. Folkestone, Burwell, South Ferriby) (Jeremiah, 1996) and Speeton (Fig. 3). In all instances sediments yielding the FAD datum of *E. monechiae* have been eroded. This subzone is also extremely condensed over much of the North Sea. To date, the evolutionary FAD of *E. monechiae* has only been documented from the Munday's Hill section, Bedfordshire (Crux, 1991; Jeremiah, 1996).

Rhagodiscus splendens Zone – LK5

Top: LAD of common *Tegulalithus tessellatus* [this study] and FAD of *Staurolithites angustus* [Jeremiah, 1996].
Base: LAD of *Ceratolithina bicornuta* [Jeremiah, 1996].
Age: Late Albian (*inflatum* MF Zone, *auritus* to *cristatum* MF Subzone).
Remarks: LK5 can be subdivided into two subzones.

Subzone LK5A

Top: LAD of common *Tegulalithus tessellatus* [this study] and FAD of *Staurolithites angustus* [Jeremiah, 1996].
Base: FAD of *Tegulalithus tessellatus* [Jeremiah, 1996] and *Gartnerago praeobliquum* [Jeremiah, 1996].
Age: Late Albian (*inflatum* MF Zone, *auritus* MF Subzone).

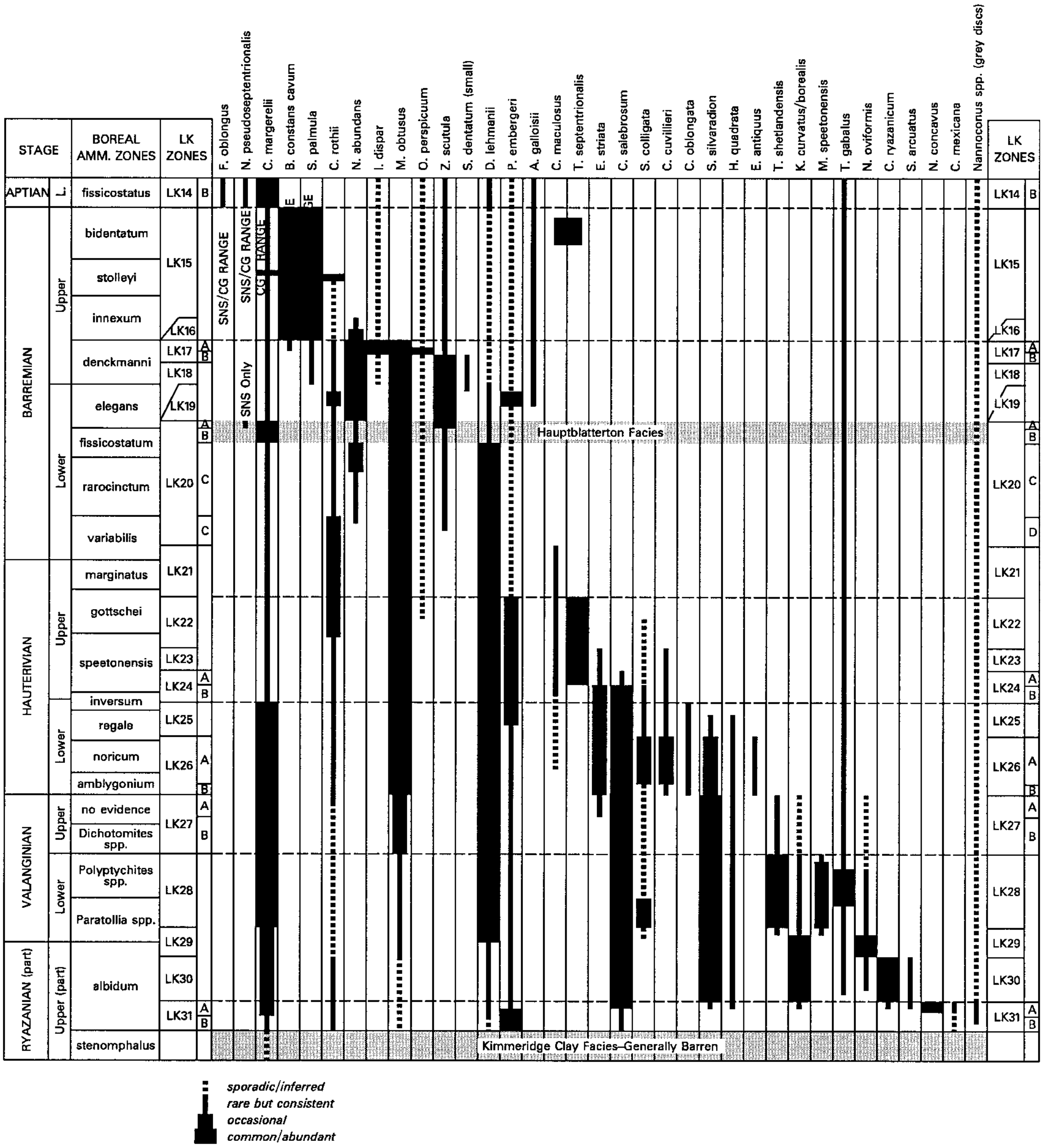


Fig. 9. Composite range chart of stratigraphically important lowermost Aptian to uppermost Ryazanian nannofossils of the North Sea Basin.

Remarks: at onshore UK sections (Burwell, Munday's Hill and Folkestone; Jeremiah, 1996) the quantitative acme of of *T. tessellatus* is recorded from this subzone. Sporadic incursions are recorded as high as LK4 (Burwell; Jeremiah, 1996 and Speeton; Fig. 3, sample DD14). In the lower abundance and diversity assemblages of the North Sea Basin common *T. tessellatus* are restricted to LK5A below the FAD of *Staurolithites angustus*. *Crepidolithus burwellensis* (large variety of Jeremiah, 1996) is restricted to LK5A.

Subzone LK5B

Top: FAD of *Tegulalithus tessellatus* [Crux, 1991] and *Gartnerago praeobliquum* [Jeremiah, 1996].

Base: LAD of *Ceratolithina bicornuta* [Jeremiah, 1996].

Age: Late Albian (early *inflatum* MF Zone, *varicosum*/*cristatum* MF Subzones).

Crucicribrum anglicum Zone – LK6

Top: LAD of *Ceratolithina bicornuta* [Jeremiah, 1996].

Base: LAD of *Braloweria boletiformis* [Crux, 1991].

Age: Middle Albian (*lautus Zone, daviesi* Subzone to late *loricatus* MF Zone, *subdelaruei* MF Subzone).

Remarks: LK6 is extremely condensed or absent over much of the North Sea and onshore Western Europe as a result of the *cristatum* erosive event (Owen, 1975). This zone can be subdivided into two subzones.

Subzone LK6A
Top: LAD of *Ceratolithina bicornuta* [Jeremiah, 1996].
Base: FAD of consistent *Axopodorhabdus albianus* and FAD of *Ceratolithina bicornuta* [this study].
Age: Middle Albian (*lautus* Zone, *daviesi* Subzone to late *loricatus* MF Zone, *meandrinus* Subzone).
Remarks: The base of Subzone BC25a of Bown *et al.* (1998) is based upon the FAD of *A. albianus*. This form is, however, recorded sporadically as low as the *intermedius* Subzone (Amédro *et al.* 1981; Jeremiah, 1996; Jakubowski, pers. comm., 1999). The FAD datum of *A. albianus*, as utilized by Bown *et al.* (1998) probably equates to the top of Subzone LK6B as defined in the current study. *Ceratolithina hamata* and *Owenia hillii* have FADs within LK6A associated with occasional/common *Parhabdolithus embergeri* (Jeremiah, 1996). The range of *C. bicornuta* has been extended into the *meandrinus* Subzone based on ammonite-dated material from the Kirchrode II borehole, onshore Germany (Jakubowski, pers. comm., 1999).

Subzone LK6B
Top: FAD of consistent *Axopodorhabdus albianus* and LDO of *Ceratolithina bicornuta* [this study].
Base: LAD of *Braloweria boletiformis* [Crux, 1991].
Age: Middle Albian (upper *loricatus* MF Zone, *subdelaruei* Subzone).

Braloweria boletiformis Zone – LK7

Top: LAD of *Braloweria boletiformis* [Crux, 1991].
Base: LAD of *Acaenolithus viriosus* [Jeremiah, 1996].
Age: Middle Albian to latest Early Albian (*loricatus* MF Zone, *niobe* MF Subzone/latest *mammillatum* MF zone, *steinmanni* MF Subzone).
Remarks: LK7 can be subdivided into two subzones.

Subzone LK7A
Top: LAD of *Braloweria boletiformis* [Jeremiah, 1996].
Base: FAD of *Ceratolithina cruxii* [Jeremiah, 1996] and *Crucicribrum anglicum* [Jeremiah, 1996].
Age: Middle Albian (*loricatus* MF Zone, *niobe* MF Subzone to *dentatus* MF Zone, *lyelli* MF Subzone).
Remarks: the FAD of consistent *Tranolithus phacelosus* occurs within the lower part of the *lyelli* Subzone (Jeremiah, 1996; Jakubowski pers. comm., 1999). It is extremely rare at this level and is prone to etching within equivalent sections throughout the North Sea Basin and onshore UK sections. Extra care is required in differentiating *T. phacelosus* from *Glaukolithus diplogrammus* within the basal Middle Albian. Rare occurrences of *T. phacelosus* have been encountered within the Early Albian (Kennedy *et al.*, 2000).

Subzone LK7B
Top: FAD of *Ceratolithina cruxii* [Jeremiah, 1996] and *Crucicribrum anglicum* [Jeremiah, 1996].
Base: LAD of *Acaenolithus viriosus* [Jeremiah, 1996].
Age: latest Early Albian (uppermost *mammillatum* MF Zone, *steinmanni* MF Subzone).
Remarks: *Prediscosphaera columnata* (restricted to the circular form of *Prediscosphaera*) has been utilized consistently by nannofossil workers as a zonal marker within the Albian (Sissingh, 1977; Perch-Nielsen, 1979; and, more recently, Bown *et al.*, 1998). The FAD of consistent *P. columnata* is found at the base of LK7B *steinmanni* ammonite-dated strata (Chamberlain's Barn section; Jeremiah, 1996 and Speeton, pers. obs.). Isolated occurrences of *P. columnata* have also been recovered from the upper part of LK8 (Bown *et al.*, 1998; Jeremiah, pers. obs.). Jakubowski (pers. comm., 1999) recorded the FAD as low as the *acuticostata* Subzone (*tardefurcata* Zone) in the Kirchrode II borehole and Kennedy *et al.* (2000) cited an intra *tardefurcata* Zonal FAD. These isolated occurrences, however, are considered too sporadic to be utilized as a reliable correlative event. By contrast, core data from North Sea Well 14/29a-4 yielded the FAD of *P. columnata* at the base of the Middle Albian associated with the FADs of *C. anglicum* and *C. cruxii*. The late FAD of *P. columnata* in this area is probably a result of the decreased preservation and diversity compared to onshore sections. Caution should therefore be used in correlating the FAD of *P. columnata* as a global marker event. Its consistent FAD in close proximity to the Lower to Middle Albian boundary is useful but, as the comments above suggest, sporadic occurrences of this form range well down into the Lower Albian.

Acaenolithus viriosus Zone – LK8

Top: LAD of *Acaenolithus viriosus* [Jeremiah, 1996].
Base: LAD of abundant *Rhagodiscus asper* [Jakubowski, 1987].
Age: Early Albian (*mammillatum*/*tardefurcata*).
Remarks: LK8 can be subdivided into three subzones.

Subzone LK8A
Top: LAD of *Acaenolithus viriosus* [Jeremiah, 1996].
Base: FAD of *Seribiscutum primitivum* [this study].
Age: Early Albian (*mammillatum* Zone, *bulliensis* Subzone to latest *tardefurcata* MF Zone, late *regularis* MF Subzone)
Comments in the North Sea Basin common *Parhabdolithus embergeri* are characteristic of this subzone. Onshore, however, this event is also recorded from Subzone LK7B (Jeremiah, 1996; West Heslerton II borehole, Appendix C). The FAD of *S. primitivum* is confirmed by *regularis* ammonite-dated material from the Kirchrode II borehole, onshore Germany (Jakubowski, pers. comm., 1999). The intra-*regularis* FAD *for S. primitivum* is confirmed by its absence from *regularis* ammonite-dated sediments from the Speeton LA1 Beds (Mitchell & Underwood, 1999) and the lower part of the *regularis* ammonite-dated sediments in the Kirchrode II borehole (Jakubowski, pers. comm., 1999). Kennedy *et al.* (2000) record the FAD of *S. primitivum* at the Tethyan Col de Pré-Guittard section from immediately below an incursion of *D. mammillatum* Zonal ammonites.

Subzone LK8B
Top: FAD of *Seribiscutum primitivum* [this study].
Base: FAD of *Acaenolithus viriosus* [Jeremiah, 1996].
Age: Early Albian (*tardefurcata* MF Zone, early *regularis* to late *schrammeni* MF Subzones).
Remarks: the basal part of the Rodby R1 Unit in the North Sea (Crittenden *et al.*, 1991) is characterized by an influx of *Repagulum parvidentatum*, *Acaenolithus galloisii* and *Tegumentum stradneri* (*Rothia striata* of Jeremiah, 1996). This same assemblage (Appendix B) is recognized from *regularis*

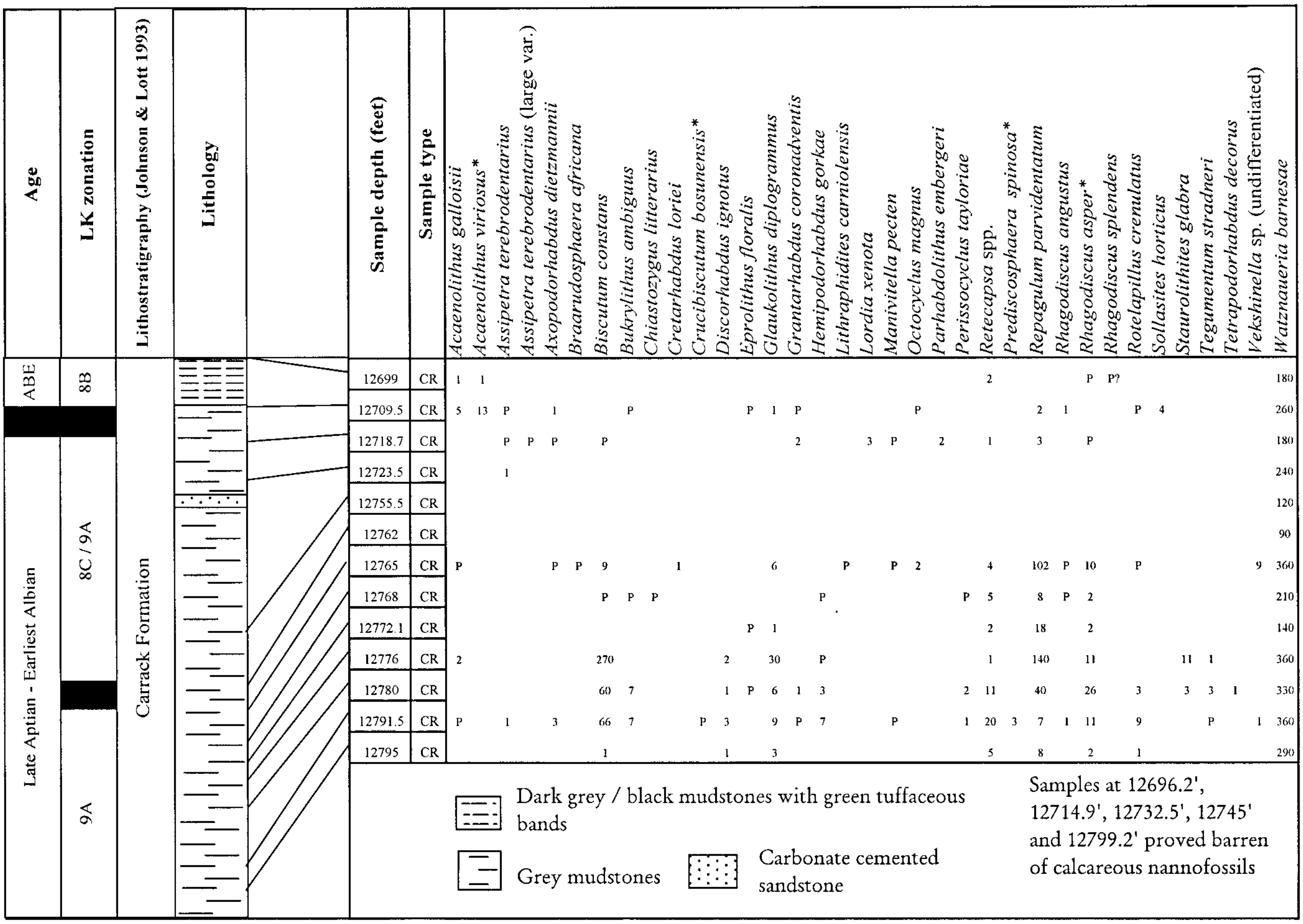


Fig. 10. Stratigraphical distribution of nannofossils from UK Moray Firth Well 15/28a-3. Note the low nannofossil diversity, a characteristic of the poorly calcareous Carrack Formation (Johnson & Lott, 1993). Palynological evidence (FDO of *Protoellipsodinium clavulum* and common *Dingodinium albertii*) suggests penetration of uppermost Aptian strata from 12762core through to 12795core.

ammonite-dated sediments from the Speeton LA1 Beds of Mitchell & Underwood (1999). The consistent FDO of the *Assipetra infracretacea*/*A. terebrodentarius* group and an isolated incursion of *Micrantholithus hoschulzii* are recorded from Subzone LK8B in the Moray Firth (identified from core and ditch-cuttings data). *Acaenolithus viriosus* was recorded as low as the top of *schrammeni* Subzonal ammonite-dated sediments from the Kirchrode II borehole, Germany (Jakubowski, pers. comm., 1999) but is absent from basal *schrammeni* Subzonal strata from Vöhrum, Germany (Jeremiah, 1996 and Bown, pers. comm.). A FAD for *A. viriosus* within the basal Albian is supported by Kennedy *et al.* (2000) based on outcrop work from southern France. At the Col de Pré-Guittard section *A. viriosus* was found to range into sediments as least as old as the *tardefurcata* Zone (*acuticostata* Subzone equivalent). Its FAD was above the highest recorded Aptian *jacobi* Zonal ammonites.

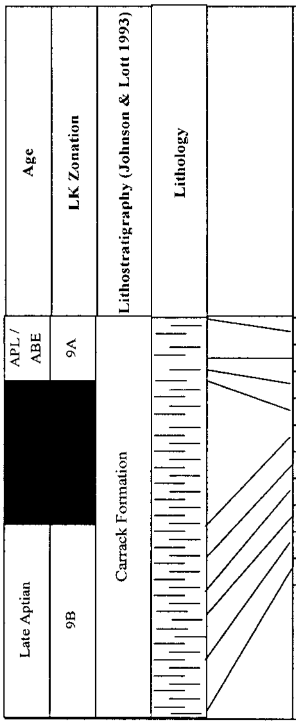
Nannofossil recovery rapidly diminishes downhole within this subzone throughout the North Sea Basin (top Carrack Formation of Johnson & Lott, 1993).

Subzone LK8C

Top: FAD of *Acaenolithus viriosus* [Jeremiah, 1996].
Base: LAD of abundant *Rhagodiscus asper* [Jakubowski, 1987].
Age: Early Albian (lower *tardefurcata* MF Zone, *schrammeni* MF Subzone).
Remarks: LK8C is rarely recognized due to the predominance of non-calcareous lithologies in the North Sea Basin. This subzone has been identified from the North Sea (Jeremiah, 1996 and this study, Fig. 10) and *schrammeni* Subzonal ammonite-dated strata at Vöhrum, onshore Germany (Jeremiah, 1996 and Bown, pers. comm.).

Rhagodiscus asper Zone – LK9

Top: LAD of abundant *Rhagodiscus asper* [Jakubowski, 1987].
Base: LAD of occasional/abundant *Crucibiscutum bosunensis* [this study].
Age: earliest Albian/Late Aptian (lowermost *tardefurcata*, *schrammeni* MF Subzone/*jacobi* MF Zone).
Remarks: LK9 has been subdivided into two subzones. Calcareous nannofossil recovery within Zone LK9 is poor throughout



Sample depth (feet)	Sample type	*Acaenolithus galloisii*	*Assipetra terebrodentarius**	*Assipetra terebrodentarius* (large var.)*	*Axopodorhabdus dietzmannii*	*Braarudosphaera africana*	*Biscutum constans*	*Bukrylithus ambiguus*	*Crucibiscutum bosunensis**	*Discorhabdus ignotus*	*Ellipsagelosphaera britannica*	*Eprolithus floralis*	*Glaukolithus diplogrammus*	*Hemipodorhabdus gorkae*	*Lithraphidites carniolensis*	*Lithraphidites* sp.	*Lordia xenota*	*Microstaurus chiastius*	*Nannoconus elongatus* gp.	*Nannoconus globulus*	*Nannoconus* spp. (undifferentiated)	*Octocyclus magnus*	*Perissocyclus tayloriae*	*Retecapsa* spp.	*Repagulum parvidentatum*	*Rhagodiscus angustus*	*Rhagodiscus asper**	*Rotelapillus crenulatus**	*Staurolithites glabra*	*Tetrapodorhabdus decorus*	*Tranolithus gabalus*	*Watznaueria barnesae*
13104.8	CR		P				160	16		8	1	9	20	34	2									3	30	1	22	1	1			180
13115.0	CR	P			P		3	1				P	42	5		9								P	P		8	3	P			270
13122.4	CR						P	2				1	P					2						8	60		28					240
13126.3	CR												1											1	3		14					240
13157.5	CR		5		1	P													P					1	180		48	1				160
13163.5	CR		3	1			13															3		5	150		4	1		1		240
13169.5	CR		3	2			7	1				P					1	P						7	19		9	15		P		210
13172.5	CR		9	5	P			2				2		P									1	15	14	1	5	5		P		270
13181.5	CR		120	30			1		P														1	1	4	1	4	1				300
13188.5	CR		1				1							1					P	P	1	2		2	33		330	72			2	160

Black mudstones

APL / ABE = Latest Aptian / Earliest Albian

Samples at 13113.5', 13118.5', 13123.5' & 13133.5' proved barren of calcareous nannofossils.

Fig. 11. Stratigraphical distribution of nannofossils from UK Moray Firth Well 15/30-9. Note the low nannofossil diversity, a characteristic of the poorly calcareous Carrack Formation (Johnson & Lott, 1993). The increase in calcareous content with the associated LK9B nannofossil assemblage appears characteristic of the Moray Firth area. Equivalent sediments are generally barren of nannofossils further south in the Central Graben.

the North Sea Basin due to the predominantly non-calcareous nature of the lithologies. Selective sampling of calcareous sediments is required in order to recognize this zone (Figs 10–11). Nannofloral recovery increases rapidly at the top of Zone LK10 (Fig. 12). Zone LK9 was recorded from basal *schrammeni* and upper *jacobi* ammonite-dated samples from Vöhrum (Jeremiah, 1996). LK9-dated sediments from the Moray Firth also yield the FDO of the palynomorph *Ovoidinium incomptum*, a form which has a documented LAD in the *jacobi* Zone (Duxbury, 1983).

Subzone LK9A

Top: LAD of abundant *Rhagodiscus asper* [Jakubowski, 1987].
Base: LAD of common *Assipetra terebrodentarius/infracretacea* group [this study].
Age: earliest Albian/Late Aptian (lowermost *tardefurcata* Zone, *schrammeni* MF Subzone to *jacobi* MF Zone).
Remarks: Abundant *R. asper* are found sporadically throughout the Middle/Late Albian. It is, however, only in LK9A and older sediments that *R. asper* is a major component of assemblages. At Vöhrum (Jeremiah, 1996) *R. asper* makes up between 15% and 30% of the total nannoflora when *Watznaueria barnesae* is discounted. It must be emphasized that sediments within this subzone, in the North Sea area, are generally non-calcareous. This has led to a depressed recording of the FDO of abundant *R. asper* in the literature (Bown *et al.*, 1998).

Subzone LK9B

Top: LAD of common of *Assipetra terebrodentarius/infracretacea* group [this study].
Base: LAD of occasional/abundant *Crucibiscutum bosunensis* [this study].
Age: Late Aptian (earliest *jacobi* MF Zone).
Remarks: a large variety of *A. terebrodentarius* is found at this level together with the FDO of rare, sporadic *Crucibiscutum bosunensis* (Fig. 11). This association has been recorded from the Outer Moray Firth in this study. Towards the base of the *A. terebrodentarius* quantitative acme, a short-lived correlative event yielding the influx of *Rotelapillus crenulatus* is recorded from throughout the Moray Firth. *R. crenulatus*, at this level, makes up some 15–20% of the nannoflora when *Watznaueria barnesae* is discounted (Fig. 11). *Braarudosphaera batilliformis* (Fig. 12) has an extremely restricted stratigraphic range within the base of LK9B where it is associated with *Braarudosphaera africana* and *B. aff. B. stenorhetha* in the Outer Moray Firth and southern North Sea basins.

Crucibiscutum bosunensis Zone – LK10

Top: LAD of common *Crucibiscutum bosunensis* [this study].
Base: LAD of common *Lithraphidites moray-firthensis* [this study].
Age: Late Aptian (*nutfieldiensis* MF Zone).
Remarks: calcareous content of Upper Aptian sediments in the North Sea Basin increases at and below Zone LK10 (Fig. 12). The delayed consistent FDOs of abundant *Rhagodiscus asper* are often recorded together with common *Crucibiscutum bosunensis* (*Crucibiscutum* cf. *C. salebrosum* of Bown *et al.*, 1998). It is probable that the top of this zone corresponds to the top of

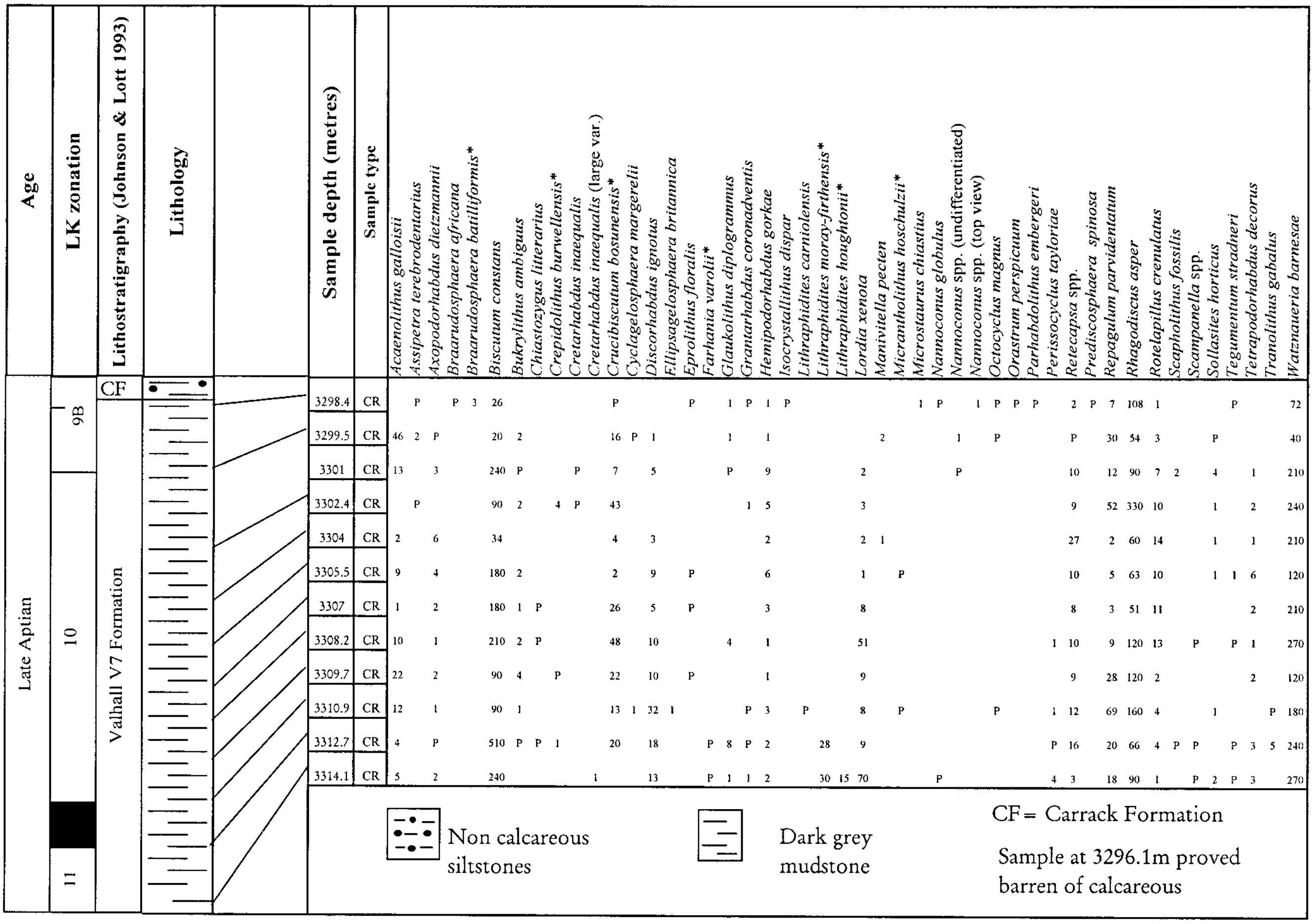


Fig. 12. Stratigraphical distribution of nannofossils from UK Moray Firth Well 21/1a-12. Note the rapid increase in abundance and diversity at the top of the Valhall Formation. Zone LK10 is not subdivided further in this well due to the absence of rare *Lithraphidites moray-firthensis*. In other nearby wells, however, rare occurrences of this form were present within LK10 and differentiation into LK10A and LK10B was possible. The *Nannoconus globulus* acme (*N. truittii* event of Mutterlose, 1989) was also not encountered. Nearby wells have proven its occurrence within the upper part of LK10A.

Zone NLK8 of Jakubowski (1987) and the intra BC21 event of Bown *et al.* (1998). *Nutfieldiensis* ammonite-dated strata from Sarstedt (Saxony Basin, Germany) and Baulking Quarry, near Farringdon, UK, yield LK10 nannofossil assemblages. This zone can be subdivided into two subzones.

Subzone LK10A

Top: LAD of common *Crucibiscutum bosunensis* [this study].
Base: LAD of *Lithraphidites moray-firthensis* [Jakubowski, 1987].
Age: Late Aptian (*nutfieldiensis* MF Zone).
Remarks: LK10A yields the FDOs of sporadic *Farhania varolii* (see Appendix B) and downhole reappearance of sporadic *Micrantholithus holschulzii* (Fig. 12). *Farhania varolii* has not been utilized as a zonal marker as proposed by Bown *et al.* (1998) (Zone BC21) due to its inconsistent occurrence, the quantitative acmes of *F. varolii* within Zones LK11 and LK13 being far more reliable datums in the North Sea Basin.

The influx of *Nannoconus globulus* is an additional correlative event towards the top of the subzone. At Sarstedt, Germany this event occurs within *nutfieldiensis* ammonite-dated sediments. This is the first downhole, basin-wide nannoconid quantitative datum recorded in the North Sea Basin. This event probably equates to the *N. truitti* event of Mutterlose (1992) and the intra BC21 *N. truitti*/*N. quadriangulus* event of Bown *et al.* (1998). This boreal nannoconid event is extremely limited in its stratigraphical extent (note not encountered in well 21/1a-12, Fig. 12) and should not be automatically correlated to similar Late ?Aptian nannoconid influxes from the Tethyan realm (Erba, 1994; Cobianchi *et al.*, 1999). This nannoconid correlation problem is specifically dealt with under the LK13B section. Other short-lived quantitative datums within LK10A include common *Crepidolithus burwellensis* (Fig. 12), common *Tranolithus gabulus* and abundant *Cyclagelosphaera rotaclypeata*. *Acaenolithus galloisii* is common throughout both LK10 and LK11.

Subzone LK10B

Top: LAD of *Lithraphidites moray-firthensis* [Jakubowski, 1987].
Base: LAD of common *Lithraphidites moray-firthensis* [this study].

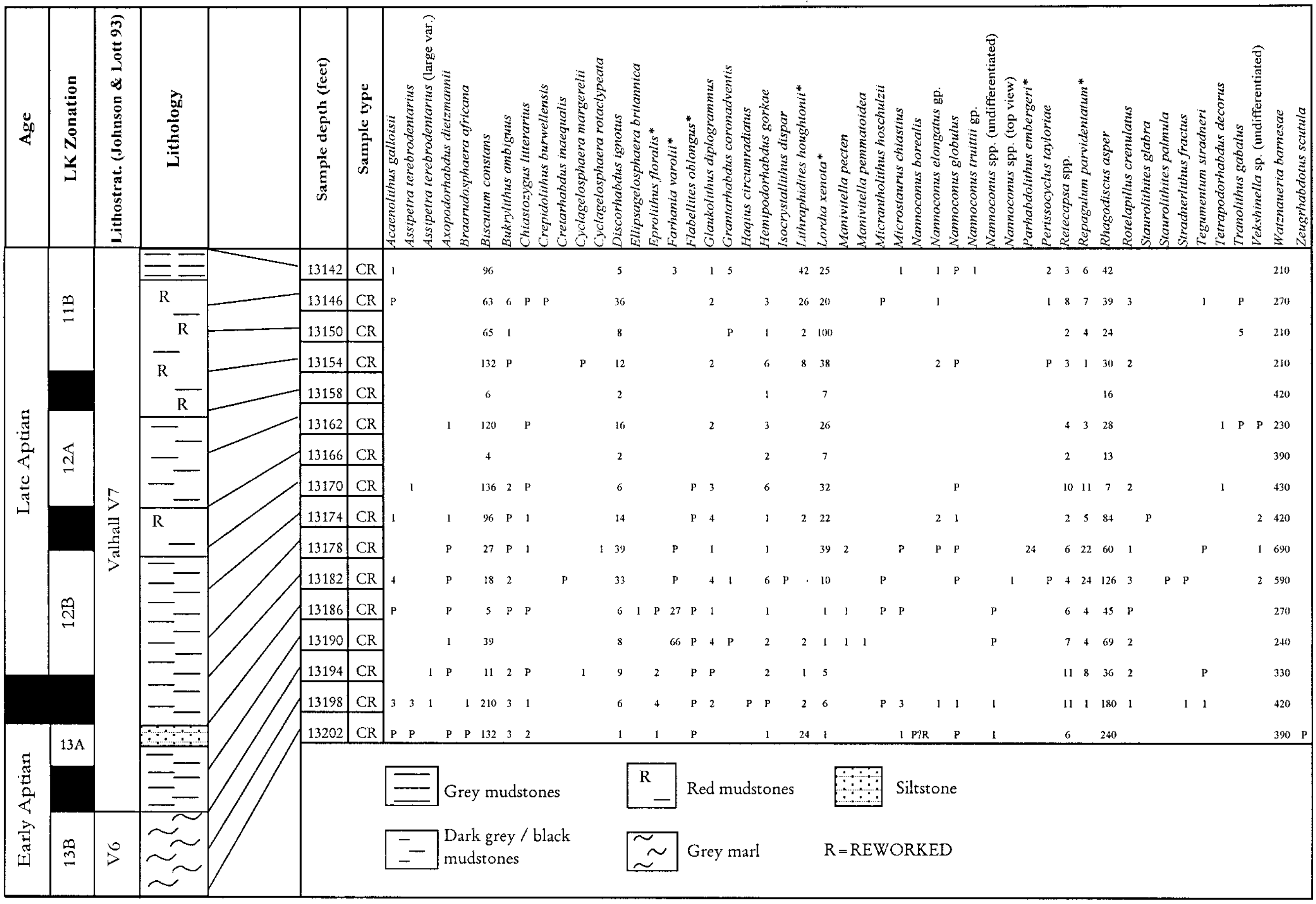


Fig. 13. Stratigraphical distribution of nannofossils from UK Moray Firth Well 15/28a-3.

Age: Late Aptian (*nutfieldiensis* MF Zone).
Remarks: in most ditch cuttings samples analysed from the North Sea Basin, LK10B is not identified, the underlying acme being far more reliable as a correlative marker. In the Outer Moray Firth, however, core evidence has confirmed a distinct separation of the FDO and its quantitative acme. The rarity and sporadic nature of *L. moray-firthensis* near its extinction datum has necessitated the downgrading of the nominate marker for top BC20 (Bown *et al.*, 1998) to subzonal status in this zonation.

Lithraphidites moray-firthensis Zone – LK11

Top: LAD of common *Lithraphidites moray-firthensis* [this study].
Base: FAD of common *Lithraphidites houghtonii* [this study] and FAD of *Lithraphidites moray-firthensis* [this study].
Age: Late Aptian (*martinioides* MF Zone).
Remarks: This zone is wholly of Late Aptian age. Previous authors (Bown *et al.*, 1998) have cautiously calibrated this event to the Early Aptian *deshayesi* Zone (Fig. 6). This zone has not been calibrated against ammonite-dated material although the age is constrained by *nutfieldiensis* ammonite-dated LK10 strata above and *martinioides* ammonite-dated LK11B sediments below. LK11 is subdivided into two subzones.

Subzone LK11A

Top: LAD of common *Lithraphidites moray-firthensis* [this study].
Base: FAD of common *Lithraphidites moray-firthensis* and LAD of common/abundant *Farhania varolii* [this study].
Age: Late Aptian (*martinioides* MF Zone).
Remarks: the FAD of common *Crucibiscutum bosunensis* occurs within this subzone and is a useful correlatable event in the Moray Firth and Central North Sea (Fig. 12). Further south, however, as in the West Heslerton II borehole (Appendix C) and Saxony Basin, this event ranges down into Zone LK12. The base of Subzone LK11A exhibits the younger of two quantitative increases of *F. varolii* (base of this event probably penetrated in 15/28a-3, fig. 13; 13142'core) in the North Sea Basin, the other defining the top of Zone LK13.

Subzone LK11B

Top: FAD of common *Lithraphidites moray-firthensis* and LAD of common/abundant *Farhania varolii* [this study].
Base: FAD of common *Lithraphidites houghtonii* and FAD of *Lithraphidites moray-firthensis* [this study].
Age: Late Aptian (*martinioides* MF Zone).
Remarks: in the Central North Sea and Outer Moray Firth red mudstones are characteristic of this subzone and the underlying

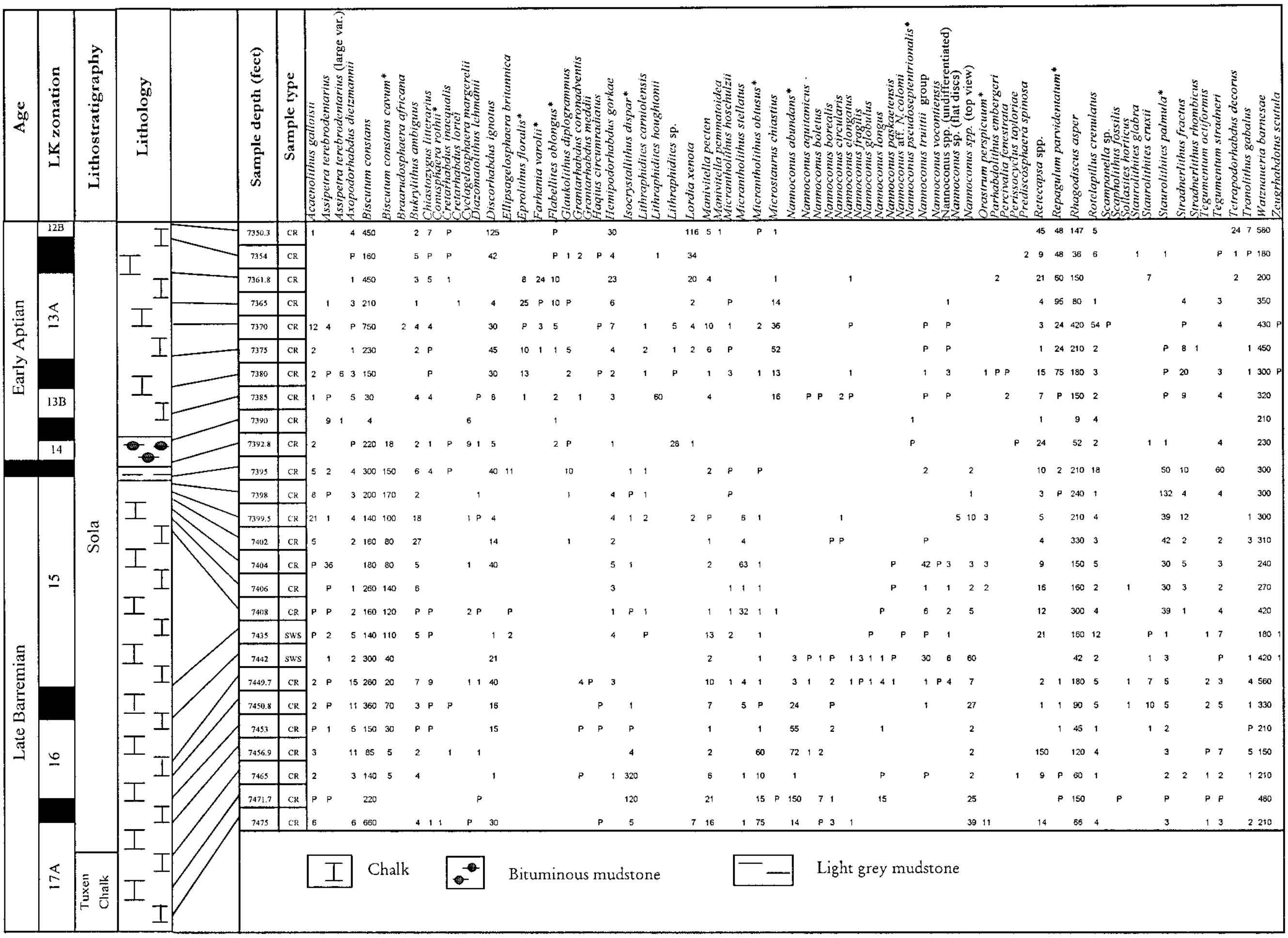


Fig. 14. Stratigraphical distribution of nannofossils from Danish Central Graben Well North-Jens 1. Note the presence of organic mudstones (Fischschiefer) and characteristic LK14 nannofossil assemblage in an otherwise chalk-dominated succession. The overlying Sola Formation (Ewadi Marl and Valhall V6 equivalent) yields a low abundance nannoconid assemblage, a feature typical of nannofloras north of the Southern North Sea area.

LK12 Zone (Fig. 13). The ammonite calibration of this subzone is confirmed by the presence of *Tropaeum drewi* (equivalent to the lower part of the *martinioides* Zone) in LK11B-dated strata from Rothenberg (Saxony Basin, Germany).

Lordia xenota Zone – LK12

Top: FAD of common *Lithraphidites houghtonii* [this study] and FAD of *Lithraphidites moray-firthensis* [this study].

Base: reappearance of common *Farhania varolii* [this study] and/or common *Eprolithus floralis* [this study].

Age: early Late Aptian to latest Early Aptian (*martinioides* to *bowerbanki* MF Zone).

Remarks: the FAD of *Prediscosphaera spinosa* (elliptical forms of *Prediscosphaera* with axial cross) appears to range into the latest Early Aptian. At Rothenberg (Saxony Basin, Germany), basal Late Aptian *Tropaeum drewi* ammonite-dated strata and topmost Early Aptian *bowerbanki* ammonite-dated samples at Gehrdener-Berg (Saxony Basin, Germany), were found to yield Zone LK12 nannofloras associated with *P. spinosa*. *Prediscosphaera spinosa* has also been observed in LK12-dated samples from the Danish North Sea (Fig. 14), West Netherlands Basin Well Spijkenisse-1 (51°50′N 04°19′E), associated with the LK12B *P. embergeri* influx, and at the West Heslerton II borehole (10.85 m). *Prediscosphaera spinosa* has, however, yet to be found below uppermost Aptian LK9 sediments within the UK Central North Sea and Moray Firth Sub-basin. Zone LK12 is subdivided into two subzones and is characterized by the abundant occurrence of *Lordia xenota*.

Subzone LK12A

Top: FAD of common/abundant *Lithraphidites houghtonii* [this study] and FAD of *Lithraphidites moray-firthensis* [this study].

Base: LAD of consistent *Flabellites oblongus* [this study].

Age: Late Aptian to latest Early Aptian (*martinioides* to *bowerbanki* MF Subzone).

Remarks: the base of the common/abundant *Lithraphidites houghtonii* quantitative event is recorded from intra *T. drewi* (*martinioides* Zone) ammonite-dated sediments at Rothenberg. *Seribiscutum dentatum* (large variety, 6–7 μm) is restricted to this subzone.

Subzone LK12B
Top: LAD of consistent *Flabellites oblongus* [this study].
Base: downhole reappearance of common *Farhania varolii* [this study] and/or common *Eprolithus floralis* [this study].
Age: latest Early Aptian (*bowerbanki* MF Zone).
Remarks: in the North Sea Basin the downhole appearance of *F. oblongus* is an important corelative datum (Fig. 13). This event has, however, proven unreliable from onshore sections where *F. oblongus* is identified from both LK10- and LK11-dated sediments. An influx of *Parhabdolithus embergeri* is encountered at the base of Subzone LK12B. Although short-lived it appears to be a basin-wide event having been recorded from the Moray Firth sub-basin (Fig. 13), onshore Germany and Netherlands.

***Eprolithus floralis* Zone – LK13**
Top: downhole reappearance of common *Farhania varolii* [this study] and/or common *Eprolithus floralis* [this study].
Base: LAD of common *Cyclagelosphaera margerelii* [this study].
Age: Early Aptian (*deshayesi*/upper *forbesi* MF Zones).
Remarks: in the North Sea Basin and onshore at Speeton and the Skegness borehole (Mutterlose, 1989) this zone corresponds to a unit of limestones and marl, the Ewaldi Marl. LK13 is subdivided into the following subzones.

Subzone LK13A
Top: downhole reappearance of common *Farhania varolii* [this study] and/or common *Eprolithus floralis* [this study].
Base: FAD of *Farhania varolii* [Mutterlose, 1991].
Age: Early Aptian (late *deshayesi* MF Zone).
Remarks: this subzone has not been identified from ammonite-bearing strata although its stratigraphic range is constrained by *deshayesi* ammonite-bearing LK13B sediments below and *bowerbanki* ammonite-dated LK12 sediments above. The FAD of *Tetrapodorhabdus decorus* occurs within this subzone (Fig. 14).

Subzone LK13B
Top: FAD of *Farhania varolii* [Mutterlose, 1991].
Base: LAD of common *Cyclagelosphaera margerelii* [this study].
Age: Early Aptian (early *deshayesi* to late *forbesi* MF Zones).
Remarks: the Tethyan marker, *Hayesites irregularis*, is confined to Zones LK13 and LK14 at southern England localities (Fig. 5). It has not been identified from any UK Central Graben section or at Speeton in this study. Its presence, however, has been confirmed from younger LK12 sediments in the West Netherlands Basin and Danish North Sea. Bischoff & Mutterlose (1998), however, also indicated the presence of *H. irregularis* (*Rucinolithus irregularis*) within the Early Aptian of Central North Sea Well 15/30-3. The presence of *H. irregularis* could not be substantiated from this well (Jeremiah, 2000) or any surrounding well in the Moray Firth area.

Diazomatolithus lehmanii is present within this subzone (Figs 4 and 5) from onshore localities and is probably indicative of a Tethyan connection with the Boreal Realm that existed at this time. At the Heslerton II borehole (Appendix C) an abundant occurrence of *D. lehmanii* was recorded from the base of LK13B (12.1 m). *Stradnerlithus fractus*, a form which is generally rare from the Boreal Lower Cretaceous is also common at levels within this subzone (Figs 4, 14).

Lithraphidites spp., including *L. houghtonii* are abundant in the lower part of this subzone associated with *Assipetra terebrodentarius* (large variety, 8–12 μm). The various forms of *Lithraphidites* spp. present at this level may have led to the misconception that *L. moray-firthensis* is restricted to the Early Aptian. The FAD of common *Repagulum parvidentatum* is at the base of LK13B (Figs 4, 5 and 14).

Lower Aptian LK13 'ewaldi Marl' (Valhall V6 of Johnson & Lott, 1993) sediments from the Vlieland Basin and Friesland Platform (northern onshore Netherlands) yield an influx of nannoconids including *N. truittii, N. globulus* and *N. vocontiensis*. An increase of nannoconids at this level is also recognized from Speeton (Fig. 4), the Skegness borehole (Mutterlose, 1989) and the Heslerton II borehole (Appendix C) but does not appear present further north in the Danish North Sea and UK Central Graben. A similar increase in wide canal nannoconids is noted in the Tethyan Realm above the Lower Aptian 'nannoconid crisis' (Erba, 1994) but has been correlated to a very short-lived, endemic Boreal Upper Aptian event, the *N. truitti* event of Mutterlose (1992), by Erba (1994) and Cobianchi *et al.* (1999).

The ammonite calibration of this subzone is confirmed by the presence of *forbesi* and *deshayesi* ammonites at Speeton (Fig. 4). This age of this zone is also confirmed in the RC1544 borehole by the presence of LK13B nannofossil assemblages from the Lower Hythe Beds (Fig. 5). These strata throughout southern England are associated with *deshayesi* zonal ammonites (Ruffell, 1992).

***Nannoconus pseudoseptentrionalis* Zone – LK14**
Top: LAD of common *Cyclagelosphaera margerelii* [this study].
Base: LAD of an influx of *Biscutum constans cavum* [this study] and/or common *Staurolithites palmula* [this study].
Age: Early Aptian (early *forbesi* to *fissicostatus* MF Zones)
Remarks: this zone is subdivided into two subzones based upon the FAD of *Eprolithus floralis*. In the Central North Sea LK14 correlates with organic, laminated mudstones commonly known as the 'Base Aptian Shale' or Fischschiefer. Onshore in England and the West Netherlands Basin, however, facies changes do not allow the organic mudstones of the offshore realm to be so easily recognized. The Fischschiefer in the North Sea Basin correlates with the Fischschiefer and *Bodei* clays of the classic German sections (Appendix B).

The base of LK14 marks a major change in the nannofossil composition. Nannofossils typical of the Tethyan Late Barremian migrate into the Boreal Realm for the first time. These forms include *Flabellites oblongus*, *Hayesites irregularis* and *Assipetra terebrodentarius* (large variety). *Conusphaera rothii*, which is recorded from the earliest Aptian of Tethys (LAD within the *weissi* MF Zone) has, however, not been recorded from the earliest Aptian of the North Sea Basin or southern England. This apparent anomaly may, however, be more a result of the poor ammonite correlation between the Boreal and Tethyan Realm over the Aptian/Barremian boundary rather than *C. rothii* exhibiting endemism.

There appears to be gathering evidence from nannofossil data that the Fischschiefer is equivalent to other anoxic shales recorded from Tethyan sections (see below). It is possible that the base of the Aptian in the Boreal Realm (taken at the base of *fissicostatus* ammonite-dated clays) correlates to the base of the Tethyan anoxic mudstones. This therefore leaves an interval of lowermost Aptian *tuarkyricus* and *weissi* Tethyan ammonite zonal sediments below the anoxic shales as correlating to an interval of Boreal, *bidentatum* ammonite-dated, latest Barremian. This suggestion is supported by the following observations.

1. The base of the Aptian marks a major change in the nannofloral composition of the North Sea Basin. Nannofossils typical of the Tethyan Late Barremian migrate into the Boreal Realm for the first time and have consistent FADs at the base of Aptian *fissicostatus* ammonite-bearing sediments. These forms include *Flabellites oblongus*, *Hayesites irregularis*, influxes of *Cyclagelosphaera margerelii* and *Assipetra terebrodentarius* (large variety) associated with a low-diversity nannoconid suite. All these nannofossil elements are also characteristic of Early Aptian Tethyan anoxic shales. Uppermost Barremian *bidentatum* ammonite-bearing sediments in the North Sea Basin yield a Boreal-restricted assemblage, very different to that recorded from the Tethyan localities (see Zone LK13 discussion). This indicates very little communication between the southern European Tethys area and the North Sea Basin during the latest Barremian.
2. The termination of these anoxic OAE1a (Arthur *et al.*, 1990) shales occurred at the same time in both the North Sea Basin and in Tethys. The reappearance of nannoconids associated with the FAD of *E. floralis* is recorded from both areas.
3. *Conusphaera rothii*, a nannofossil typical of earliest Aptian *tuarkyricus* and *weissi* Tethyan ammonite zonal sediments has a LAD before the inception of the OAE1a anoxic event (Rio Argos section, Caracava, SE Spain (Hoedemaeker & Leereveld, 1995). *Conusphaera rothii* is also absent from the equivalent North Sea Fischschiefer facies.

The apparent calibration problem between the base Aptian of the North Sea and Tethys can perhaps be explained by the earlier evolution of *Prodeshayesites* in the southern European Tethyan Realm. An endemic Boreal nannofossil and heteromorph ammonite suite persisted in the North Sea Basin until the Lower Aptian sea level rise, OAE1a (Arthur *et al.*, 1990), and the resultant introduction of a Tethyan micro- and macrofaunal element with its associated organic mudstone lithologies. This idea contrasts markedly with the current views on Boreal/Tethyan correlations and more detailed ammonite and nannofossil work from Tethyan localities is required to support this theory.

Subzone LK14A

Top: LAD of common/abundant *Cyclagelosphaera margerelii* [this study].
Base: FAD of *Eprolithus floralis* [Taylor, 1982].
Age: Early Aptian (lower *forbesi* MF Zone).
Remarks: this subzone is rarely recognized in routine analyses but has been positively identified in core from the topmost Fischschiefer (unreleased well, Central North Sea), *forbesi* ammonite-dated material at Speeton (Bed LA6, Fig. 4) and the Atherfield Clay (Fig. 5).

The FAD of *Eprolithus floralis* is an extremely useful cosmopolitan datum. Unfortunately the widespread use of the inception of *E. floralis* as marking the base of the Tethyan Late Aptian (base criteria for the Late Aptian *Parhabdolithus angustus* Zone of Thierstein, 1973) (Erba, 1994; Cobianchi *et al.*, 1999) has led to confusion in correlations of Boreal and Tethyan sections. Samples analysed by the author from the Rio Argos section, Caracava, SE Spain (Hoedemaeker & Leereveld, 1995) confirmed the FAD of *E. floralis* immediately above black mudstones attributed to the global oceanic anoxic event OAE 1a (Arthur *et al.*, 1990). The same sequence of events is recorded from the Selli Level of Italy (Cobianchi *et al.*, 1999), the Middle Almadich Member of SE Spain (Aguado *et al.*, 1999) and the Fischschiefer of the North Sea. The presence of *E. floralis* immediately above the so-called 'nannoconid crisis' (Erba, 1994) is therefore a common event worldwide. The FAD of *E. floralis* immediately above these anoxic levels thus indicates that the Selli Level, Middle Almadich Member and other so-called early Aptian OAE 1a mudstones are no younger than the earliest Aptian intra-*forbesi* Zone. No evidence of an unconformity at the Lower to Upper Aptian boundary is cited from Tethyan localities (Erba, 1994; Cobianchi *et al.*, 1999). It is therefore considered probable that the so-called 'Upper Aptian' sediments immediately above the anoxic event at those Tethyan localities are still of Early Aptian age.

Subzone LK14B

Top: FAD of *Eprolithus floralis* [Taylor, 1982].
Base: LAD of influx of *Biscutum constans cavum* [this study] and/or common *Staurolithites palmula* [this study].
Age: Early Aptian (lower *forbesi* to *fissicostatus* MF Zones).
Remarks: this subzone constitutes the majority of the Fischschiefer facies in the North Sea Basin. *Nannoconus pseudoseptentrionalis*, a potential ancestor of *Eprolithus floralis* is characteristic of this subzone in England and over much of the North Sea. In the northern North Sea (e.g. Norwegian well 31/3-3), extremely rare occurrences of both *Flabellites oblongus* and *N. pseudoseptentrionalis* have been recorded from below the Fischschiefer within the latest Barremian. *Nannoconus pseudoseptentrionalis* also has a short-lived incursion within the Lower Barremian anoxic Hauptblatterton facies of the southern North Sea and Saxony Basin. Large forms of *Assipetra terebrodentarius* are common at levels within the Fischschiefer as they are in Tethyan sediments of equivalent age (Aguado *et al.*, 1999)

In the southern England sections studied, common *Ellipsagelosphaera britannica* are also recorded (Fig. 5 and Appendix B), a result of Upper Jurassic reworking which is prevalent in the area. The high relative abundances of *E. britannica* documented from the Atherfield Clay on the Isle of Wight (Bown *et al.*, 1998) are probably accentuated by similar Upper Jurassic reworking. Modern day estuarine nannofossil assemblages from the nearby Solent yield over 30% of Jurassic forms, again dominated by *E. britannica*. An Early Aptian *E. britannica* event is not recorded from Speeton, the Heslerton II borehole, the North Sea Basin or onshore Netherlands.

This subzone has been found to yield basal Aptian *fissicostatus* ammonites at Speeton (Fig. 4), the basal Aptian ammonite, *Prodeshayesites bodei* from Alstatte in the '*bodei*' clays (Saxony Basin, Germany) and slightly younger *forbesi* ammonites in the Atherfield Clay.

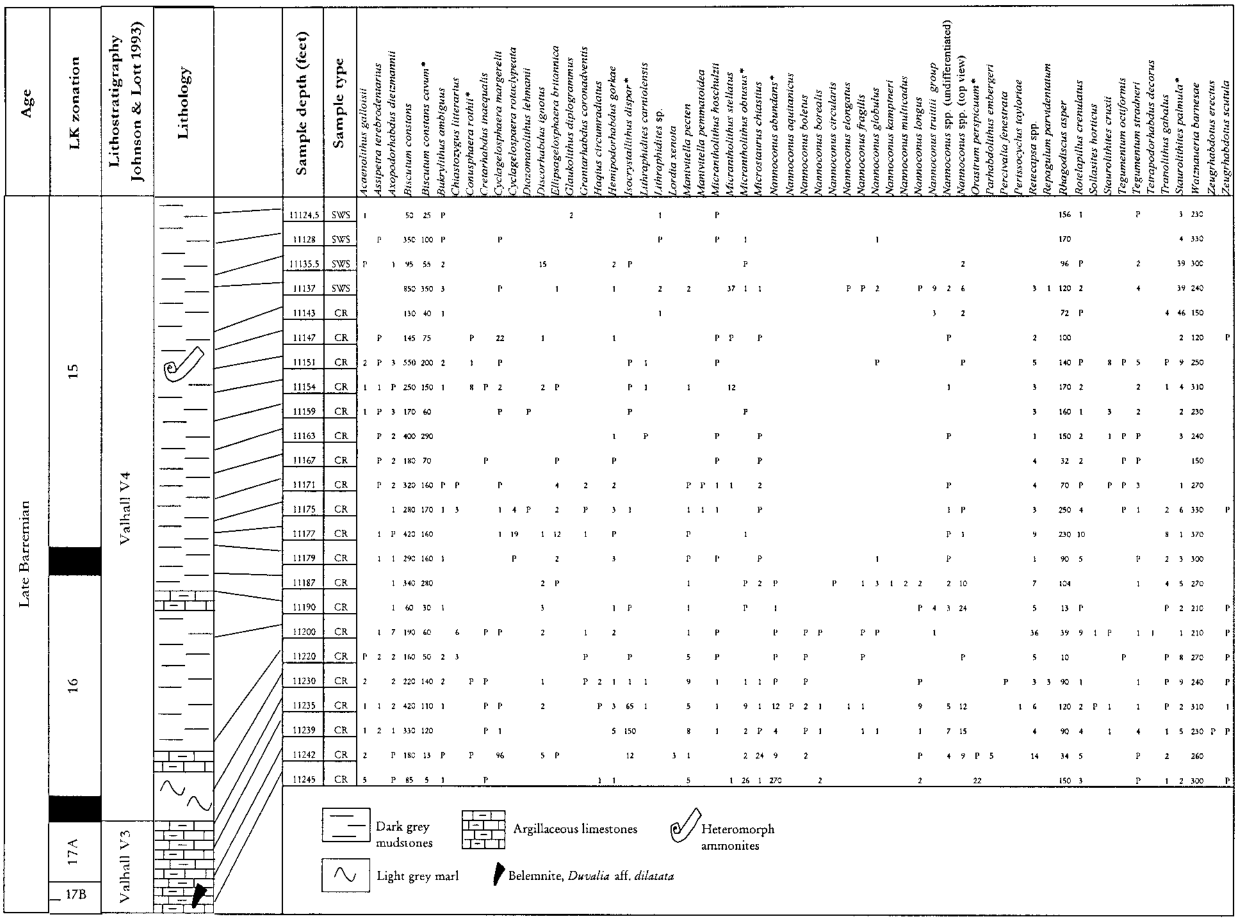


Fig. 15. Stratigraphical distribution of nannofossils from UK Central Graben Well 22/26a-2.

Staurolithites palmula Zone – LK15

Top: LAD of influx of *Biscutum constans cavum* [this study] and/or common *Staurolithites palmula* [this study].
Base: LAD of *Nannoconus abundans* [Taylor, 1982].
Age: Late Barremian (*bidentatum* to *?pingue* MF Zones).
Remarks: *Bidentatum* ammonite-bearing strata from the top of the Late Barremian at Speeton are found to yield an LK15 endemic Boreal nannofossil association. Short-lived warm water incursions are recorded (probably via the proto-Atlantic) but, in general, the nannofloral assemblages cannot be directly correlated with Tethyan sections over much of the Late Barremian. Tethyan incursions are recorded from the upper part of LK15, one of which is characterized by a short-lived influx of *Micrantholithus stellatus* (Fig. 15), a form common throughout the latest Barremian of southern Spain (Aguado *et al*., 1997). A brief incursion of *Conusphara rothii* is recorded from a narrow horizon (Figs 15 and 16) within the Upper Barremian of the North Sea Basin. This event is also noted by Gallagher in Bown *et al.* (1998) (*C.* cf. *C. rothii,* squat morphology) but was considered a Lower Aptian '*bodei*' Clay equivalent event. This nannofloral event has, however, been recorded with Upper Barremian heteromorph ammonites *Hemihoplites*, *Camereiceras* and *Heteroceras* sp. in Central North Sea Well 22/26a-2 (Fig. 15). This ammonite assemblage is more indicative of the Tethyan *feraudinianus* MF Zone (equates to the Boreal *stolleyi* MF Zone; P. Rawson, pers. comm.) and, together with the associated *C. rothii*, is good evidence for a warm-water incursion into the Boreal Realm during *stolleyi* times. *Diazomatolithus lehmanii* and *Isocrystallithus dispar*, forms characteristic of the Tethyan Late Barremian, occur sporadically throughout LK15 (Figs 14 and 15).

Thin organic horizons very similar in lithology to the overlying Fischschiefer are also developed yielding abundant *Cyclagelosphaera margerelii* (Figs 15 and 16). Unlike the Fischschiefer, however, influxes of large *Ellipsagelosphaera britannica* and common *Cyclagelosphaera rotaclypeata* are also recorded (Fig. 15). The *E. britannica* influx was also documented by Gallagher in Bown *et al.* (1998) but was considered an Early Aptian event. The conspicuous large *B. constans* event of Gallagher in Bown *et al.* (1998) probably equates to the top *B. constans cavum* influx in this study. *Tegumentum octiformis* has its LAD towards the top of LK15.

Nannoconus abundans Zone – LK16

Top: LAD of *Nannoconus abundans* [Taylor, 1982].
Base: LAD of common *Isocrystallithus dispar* [this study].
Age: Late Barremian (*?pingue* MF Zone).

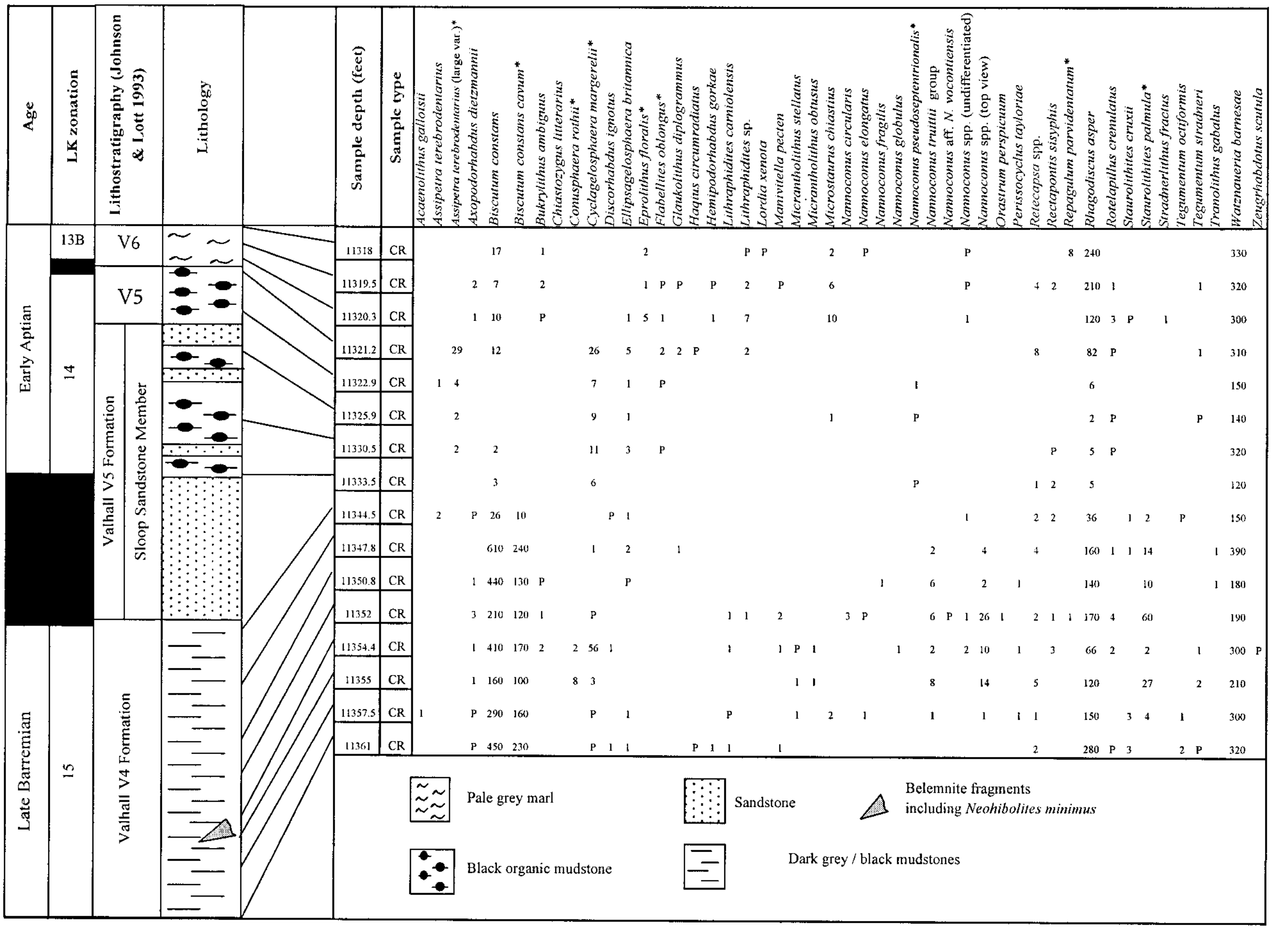


Fig. 16. Stratigraphical distribution of nannofossils from UK Moray Firth Well 21/2-6.

Remarks: the top of this zone marks a major downhole change in nannofossil composition in the Central and Southern North Sea. A diverse, Boreal endemic nannoconid assemblage including *N. abundans, N. borealis, N. boletus* and *N. longus* all have their consistent LADs at this level (Figs 14 and 15). LK16 differentiation is, however, complicated in the Northern North Sea (Fig. 17) by the extremely rare occurrence of *N. abundans* above LK17. Its extreme rarity usually precludes LK16 from being identified as a definitive zone in this area. Bown *et al.* (1998) record the LAD of *N. abundans* within the Early Aptian of the Heslerton II borehole (depth not quoted). This isolated record may be a result of reworking since this occurrence could not be substantiated in this study (Appendix C). Gallagher in Bown *et al.* (1998), by contrast, indicated the FDO of *N. abundans* below both the *C. rothii* incursion and *Ellipsagelosphaera britannica* influx. This sequence of events is supported in the present study. The age attributed to these events and calibration with the ammonite zonation is, however, markedly different.

Nannoconus borealis is not utilized as a zonal marker in this study due to its sporadic occurrence over the majority of its range. Bown *et al.* (1998) used both the FAD and LAD of *N. borealis* as zonal markers. In this study the highest consistent LAD is associated with the overall downhole increase in nannoconid diversity at the top of Zone LK16 (Figs 14 and 15). The consistent LAD of *N. borealis* is utilized as supportive evidence for top Zone LK16 but the associated presence of *N. abundans* is considered a more reliable nannofossil datum in the North Sea Basin. *Nannoconus borealis* was absent from the West Heslerton II borehole and extremely rare in the northern North Sea and onshore Netherlands.

Additional correlative events include the downhole reappearance of *Conusphaera rothii* associated with the FDO of common *N. abundans* towards the base of this zone (also documented by Gallagher in Bown *et al.*, 1998).

Micrantholithus obtusus Zone – LK17

Top: LAD of common *Isocrystallithus dispar* [this study].
Base: LAD of common *Zeugrhabdotus scutula* [Bown *et al.*, 1998].
Age: Late Barremian (*?pingue* MF Zone).
Remarks: LK17 is subdivided into two subzones.

Subzone LK17A

Top: LAD of common *Isocrystallithus dispar* [this study].
Base: FAD of common *Isocrystallithus dispar* [this study].
Age: Late Barremian (*?pingue* MF Zone).

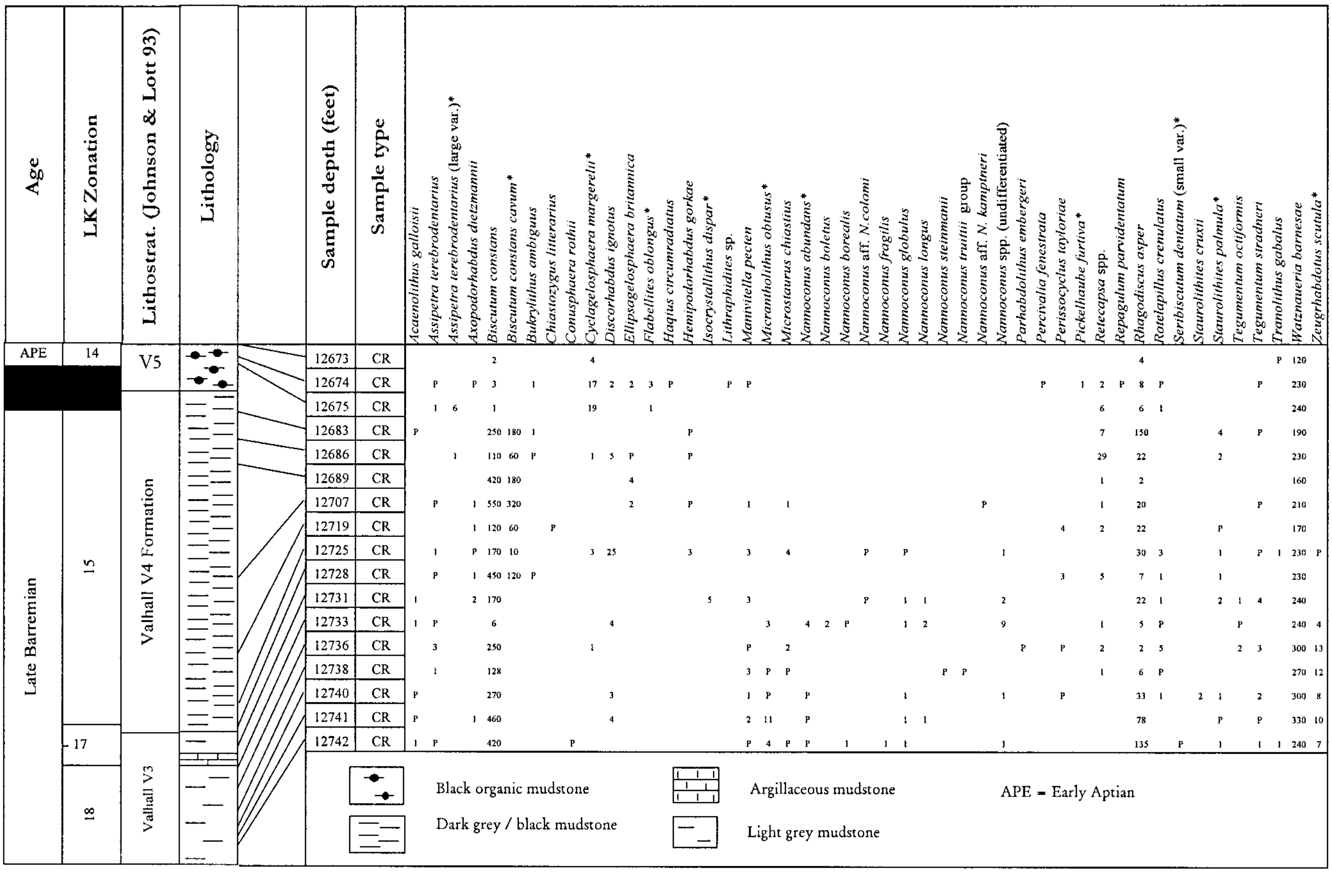


Fig. 17. Stratigraphical distribution of nannofossils from UK Viking Graben Well 3/18c-1. Note the low abundance and diversity of nannoconids within LK17 and LK18 compared to equivalent sections from the Moray Firth and Central Graben wells.

Remarks: *Isocrystallithus dispar* is recorded throughout the Albian to Barremian of Tethys (Rawson & Jeremiah, 2001) but is rare in the North Sea Basin. The LK17A incursion is an exception. This short-lived quantitative acme of *Isocrystallithus dispar* has been recorded in core from Central North Sea well 22/26a-2 (Fig. 15) with a Tethyan indicator belemnite, *Duvalia* aff. *robusta,* which supports a warm-water connection with the North Sea Basin at this time probably via a proto-Atlantic route (Rawson & Jeremiah, 2001). Additional correlative events include an incursion of *Orastrum perspicuum* at the base of this subzone (Fig. 15). The FDO occurrence of common *Micrantholithus obtusus* approximates to this subzone (Figs 14 and 15). The *I. dispar* acme event has been identified as far south as the offshore Netherlands L Block (Vlieland Basin) but has yet to be recorded from the Saxony Basin.

Subzone LK17B

Top: FAD of common *Isocrystallithus dispar* [this study].
Base: LAD of common *Zeugrhabdotus scutula* [Bown *et al.*, 1998].
Age: Late Barremian (?*denkmanni* MF Zone).
Remarks: The nannofloral assemblage is characterized by a diverse nannoconid assemblage dominated by *N. abundans, N. longus, N. boletus* and *N. bucheri* group.

Zeugrhabdotus scutula Zone – LK18

Top: LAD of common *Zeugrhabdotus scutula* [Bown *et al.*, 1998].
Base: LAD of consistent *Diazomatolithus lehmanii* [this study].
Age: Late Barremian (?*denckmanni* MF Zones).
Comments: the FDO of *Crucibiscutum salebrosum* (large variety, Crux, 1989) is towards the base of LK18 (Fig. 18).

Diazomatolithus lehmanii Zone – LK19

Top: LAD of consistent *Diazomatolithus lehmanii* [this study].
Base: LAD of short-lived acme of *Cyclagelosphaera margerelii* [this study].
Age: Early Barremian (*elegans* MF Zone).
Comments: the identification of LK19 based solely on the presence of *D. lehmanii* should be used with extreme caution. Sporadic occurrences of *D. lehmanii* are recorded throughout the Late Barremian of the North Sea Basin. Further south in southern Britain, with increased Tethyan influence, *D. lehmanii* is recorded consistently in Lower Aptian strata. Identification of the associated *Zeugrhabdotus scutula* acme is essential, preferably with one of the following short-lived quantitative datums documented below which can be correlated throughout the Outer Moray Firth, Central North Sea and Tuxen Formation of

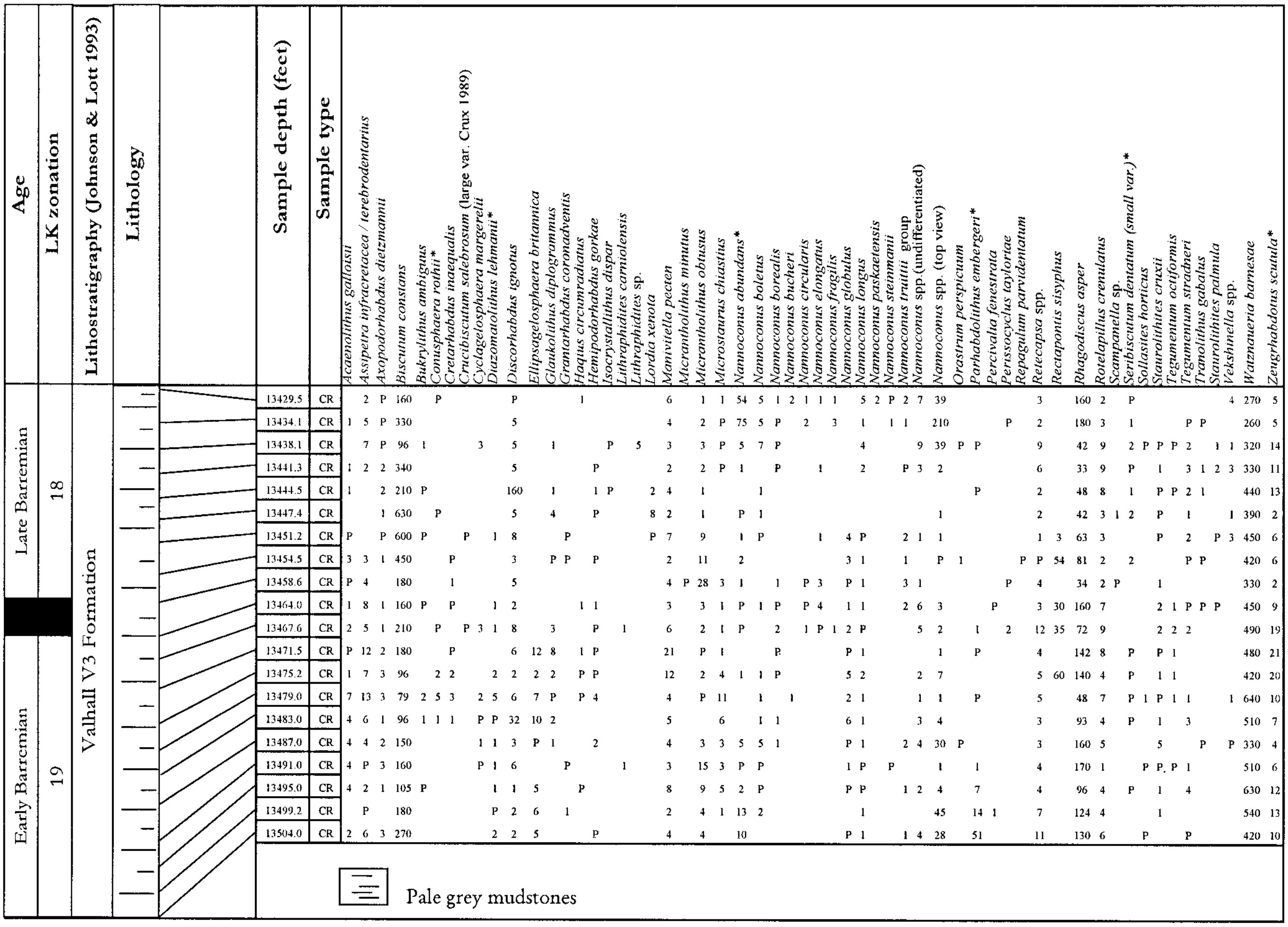


Fig. 18. Stratigraphical distribution of nannofossils from UK Moray Firth Well 15/29a-5.

the Danish North Sea. These events in descending order are as follows:

i. incursion of common *Parhabdolithus embergeri* (Figs 18 and 19);
ii. incursion of common *Sollasites horticus* (Fig. 19). The FAD of *Acaenolithus galloisii* (*Acaenolithus* sp. 1 of Bown *et al.*, 1998) lies within LK19 associated with the *Sollasites horticus* incursion (Fig. 19);
iii. incursion of common *Percivalia fenestrata* (Fig. 19).

In the Netherlands onshore sections investigated the LAD of consistent *D. lehmanii* appears depressed. Here, the LAD of consistent *D. lehmanii* (common at this level) is found immediately prior to the onset of the Hauptblatterton facies (top Subzone LK20C).

Conusphaera rothii Zone – LK20

Top: LAD of short-lived acme of *Cyclagelosphaera margerelii* [this study].
Base: LAD of *Clepsilithus maculosus* [Crux, 1989].
Age: Early Barremian (lower *elegans*/upper *variabilis* MF Zones).
Remarks: LK20 is subdivided into three subzones.

Subzone LK20A

Top: LAD of short-lived acme of *Cyclagelosphaera margerelii* [this study].
Base: FAD of common *Zeugrhabdotus scutula* [Bown *et al.*, 1998].
Age: Early Barremian (lower *elegans* MF Zone).
Remarks: the downhole reappearance of an acme of *C. margerelii* can be correlated to a brief period of anoxia in the Saxony Basin, the Hauptblatterton facies. Gallagher in Bown *et al.* (1998) considered the base of the *Zeugrhabdotus scutula* acme to lie below the Hauptblatterton facies. Core data from the West Netherlands Basin and western Saxony Basin indicate the base common occurrence of *Z. scutula* is located within the upper part of the Hauptblatterton facies. A short-lived incursion of *Nannoconus pseudoseptentrionalis* is characteristic of this subzone from the West Netherlands Basin, Saxony Basin and Speeton *elegans* ammonite-dated LB1A Beds (Rutledge, pers. comm., 2000). This event has yet to be identified from the Central North Sea.

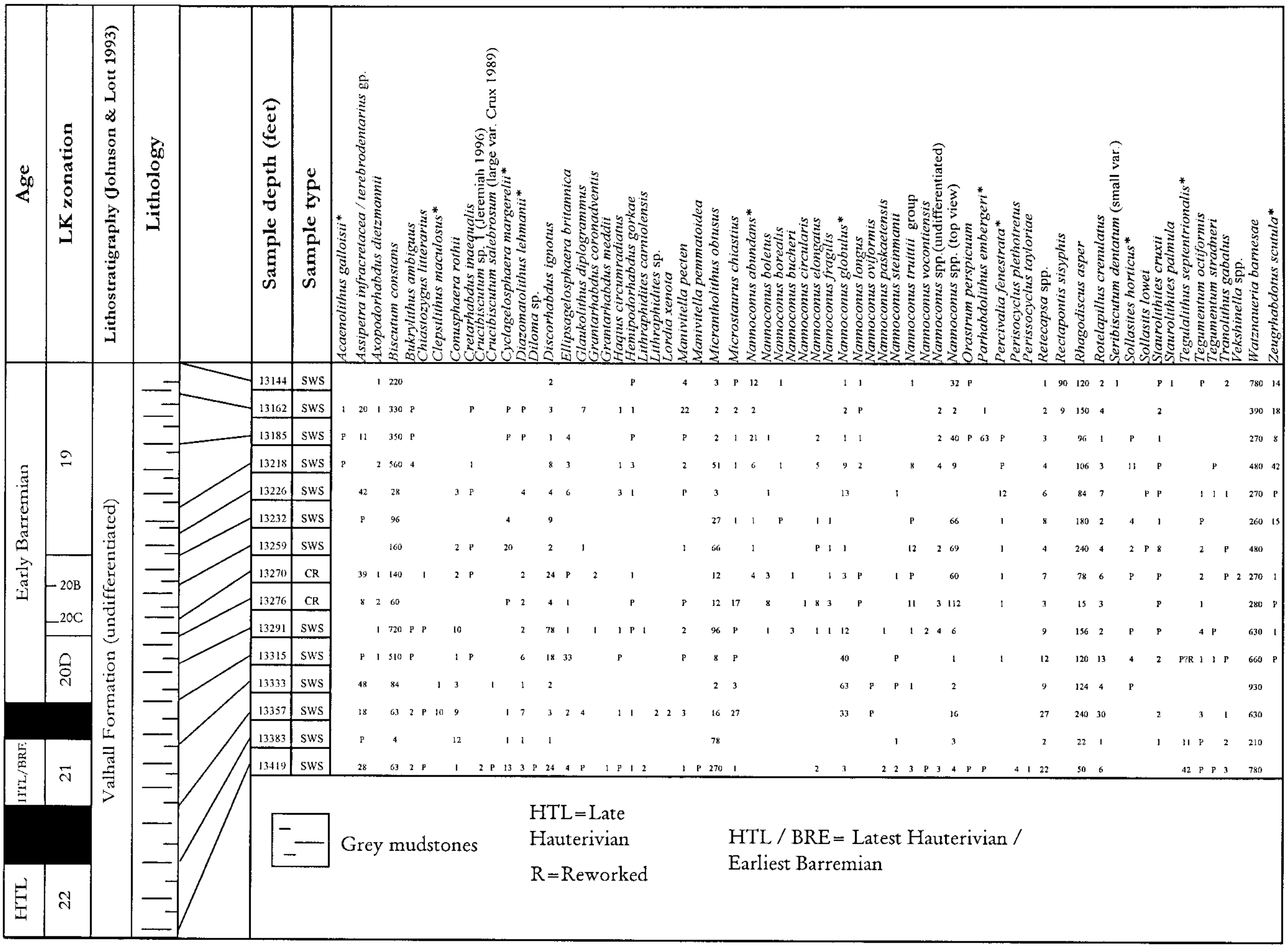


Fig. 19. Stratigraphical distribution of nannofossils from UK Moray Firth Well 15/25a-2 (Early Barremian / Late Hauterivian).

Subzone LK20B
Top: FAD of common *Zeugrhabdotus scutula* [Bown *et al.*, 1998].
Base: FAD of short-lived acme of *Cyclagelospheara margerelii* [this study].
Age: Early Barremian (upper *fissicostatum* MF Zones).
Remarks: the lower part of the Hauptblatterton facies in the Saxony Basin correlates to the Munk Marl as utilized in the UK North Sea. Samples provided by J. Ineson (Danish Geological Survey) from Danish Well N. Jens-1 have proven that the type Munk Marl (Jensen *et al.*, 1986) is restricted to an intra-LK20B Subzonal age. In the Saxony Basin the LAD of common to abundant *Assipetra terebrodentarius* is an additional correlative event in the lower part of this subzone.

Subzone LK20C
Top: FAD of short-lived acme of *Cycalgelospheara margerelii* [this study].
Base: FAD of *Nannoconus abundans* [Taylor, 1982].
Age: Early Barremian (lower *fissicostatum*/*rarocinctum* MF Zones).
Remarks: *Nannoconus abundans* has a sporadic occurrence towards the base of its range (Fig. 19) and should be utilized with caution. In cored sections from the Friesland Platform and western margins of the Saxony Basin, onshore Netherlands, *N. abundans*, along with other nannoconid species, is entirely absent from LK20-dated Lower Barremian sediments. Further east into the Saxony Basin nannoconid abundance increases and the FAD of *N. abundans* is found to correlate with the FAD of an incursion of common to abundant *Assipetra terebrodentarius*. The base of the *A. terebrodentarius* event is utilized as an alternative LK20C marker in the onshore Netherlands, particularly in the absence of *N. abundans*. In this study, the FAD of *N. abundans* is only utilized as a subzonal marker in contrast to the Zone BC13 application of Bown *et al.* (1998).

Subzone LK20D
Top: FAD of *Nannoconus abundans* [Taylor, 1982].
Base: LAD of *Clepsilithus maculosus* [Crux, 1989].
Age: Early Barremian (upper *variabilis* MF Zone).
Remarks: in the North Sea Basin LK20C and LK21 exhibit a low diversity nannoconid assemblage dominated by *Nannoconus globulus* (Fig. 19), whilst in the Northern North Sea *Nannoconus steinmannii*, a supposed warm-water indicator, predominates.

Clepsilithus maculosus Zone – LK21

Top: LAD of *Clepsilithus maculosus* [Crux, 1989].
Base: LAD of *Tegulalithus septentrionalis* [Jakubowski, 1987].
Age: earliest Barremian/latest Hauterivian (lower *variabilis*/upper *gottschei* MF Zones).
Remarks: LK21 and LK22 sediments are characterized by the consistent occurrence of abundant *Assipetra infracretacea*.

Tegulalithus septentrionalis Zone – LK22

Top: LAD of *Tegulalithus septentrionalis* [Jakubowski, 1987].
Base: LAD of *Eiffellithus striatus* [Bown *et al.*, 1998].
Age: Late Hauterivian (*gottschei*/upper *speetonensis* MF Zones).
Remarks: the LAD of *Tegulalithus septentrionalis* is an abrupt event in the North Sea Basin. No differentiation of the NLK14 (FDO *T. septentrionalis*) and NLK15 (common/abundant *T. septentrionalis*) Zones of Jakubowski (1987) is made. Extremely rare occurrences of *T. septentrionalis* above the common to abundant occurrence are recorded (Fig. 19) but these are, at present, interpreted as reworked.

Nannoconid diversity is generally low with *Nannoconus steinmannii* predominant. In the Danish Sector of the Central North Sea *Parhabdolithus embergeri* is common.

Speetonia colligata was utilized by Bown *et al.* (1998) as a latest Hauterivian marker (intra BC11) above the FDO of *T. septentrionalis.* In the current study *S. colligata* has only been recorded sporadically as high as LK22. Records above the LAD of *T. septentrionalis* may be a result of reworking.

Eiffellithus striatus Zone – LK23

Top: LAD of *Eiffellithus striatus* [Bown *et al.*, 1998].
Base: LAD of consistent *Crucibiscutum salebrosum* [this study].
Age: Late Hauterivian (*speetonensis* MF Zone).
Remarks: The LAD of *Cruciellipsis cuvillieri* occurs within this zone.

Cruciellipsis cuvillieri Zone – LK24

Top: LAD of consistent *Crucibiscutum salebrosum* [this study].
Base: LAD of common to abundant *Cyclagelosphaera margerelii* [Jakubowski, 1987] and/or LAD of *Calcicalithina oblongata* [this study].
Age: Late Hauterivian/latest Early Hauterivian (*speetonensis*/*inversum* MF Zone).
Remarks: this zone can be subdivided into two subzones.

Subzone LK24A

Top: LAD of consistent *Crucibiscutum salebrosum* [this study].
Base: FAD of *Tegulalithus septentrionalis* [Jakubowski, 1987].
Age: Late Hauterivian (*speetonensis* MF Zone).

Subzone LK24B

Top: FAD of *Tegulalithus septentrionalis* [Jakubowski, 1987].
Base: LAD of common to abundant *Cyclagelosphaera margerelii* [Jakubowski, 1987] and/or LAD of *Calcicalithina oblongata* [this study].
Age: Late Hauterivian (*inversum* MF Zone].

Cyclagelosphaera margerelii Zone – LK25

Top: LAD of common to abundant *Cyclagelosphaera margerelii* [Jakubowski, 1987] and/or FDO of *Calcicalithina oblongata* [this study].
Base: LAD of *Eprolithus antiquus* [Crux, 1989].
Age: Early Hauterivian (*inversum* to upper *regale* MF Zone).
Remarks: in the southern North Sea and onshore UK sections *C. oblongata* is absent. Further north, however, this form is characteristic of the Early Hauterivian and probably indicates a connection with Tethyan waters via a proto-Atlantic seaway (Figs 20 and 21). In the Moray Firth the LADs of *C. oblongata* and the *C. margerelii* acme coincide (Fig. 20). In the North Viking Graben, West of Shetlands Basin and offshore northern Norway the *C. margerelii* acme is sporadic and unreliable as a marker event (pers. obs. and Slinnabanken core in Crux, 1989). *Calcicalithina oblongata* remains prevalent and is a useful alternative marker in these areas for top LK25.

Secondary markers of correlative significance include the LAD of *Stradnerlithus silvaradius* towards the top of this zone and the boreal LAD of *Helenea quadrata.* The nannoconid assemblage is characterized by *Nannoconus steinmanni*, *Nannoconus vocontiensis* and *Nannoconus cornuta*.

Specimens of the ammonite genus, *Aegocrioceras* sp. (Rawson, pers. comm., 2000, equivalent to the *inversum* ammonite Zone) were found at the base of the Guildehaus Sandstone (Kemper, 1992) associated with abundant *Cyclagelosphaera margerelii, Eiffellithus striata* and *Crucibiscutum salebrosum* in Saxony Basin Well Sleen Dommerskanaal-1 (Adrichem Boogaert & Kouwe, 1993; 52°41′N 06°52′E). Elsewhere in the western Saxony basin (Wells De-Wijk-5 [52°42′N 06°24′E], Beilen-2 [52°48′N 06°30′E] and Tubbergen-6 [52°25′N 06°54′E) Zone LK25 nannofossil assemblages have also been recorded from core in the lower part of the Guildehaus Sandstone. This is consistent with the identification of a varied *Aegocrioceras* spp. ammonite assemblage described by Kemper (1992) from the lower Guildehaus Sandstone at Guildehaus, Germany.

Eprolithus antiquus Zone – LK26

Top: LAD of *Eprolithus antiquus* [Crux, 1989].
Base: LAD of *Triquetrorhabdulus shetlandensis* [Bown *et al.*, 1998].
Age: Early Hauterivian (lower *regale*/*amblygonium* MF Zones).
Remarks: This zone can be subdivided into two subzones.

Subzone LK26A

Top: LAD of *Eprolithus antiquus* [Crux, 1989].
Base: FAD of *E. antiquus* [Crux, 1989].
Age: Early Hauterivian (lower *regale*/upper *amblygonium* MF Zones).
Remarks: this zone is characterized by sporadic incursions of common *Speetonia colligata*, common *Cruciellipsis cuvillieri* and *Sollasites lowei*.

Subzone LK26B

Top: FAD of *Eprolithus antiquus* [Crux, 1989].
Base: LAD of *Triquetrorhabdulus shetlandensis* [Bown *et al.*, 1998].

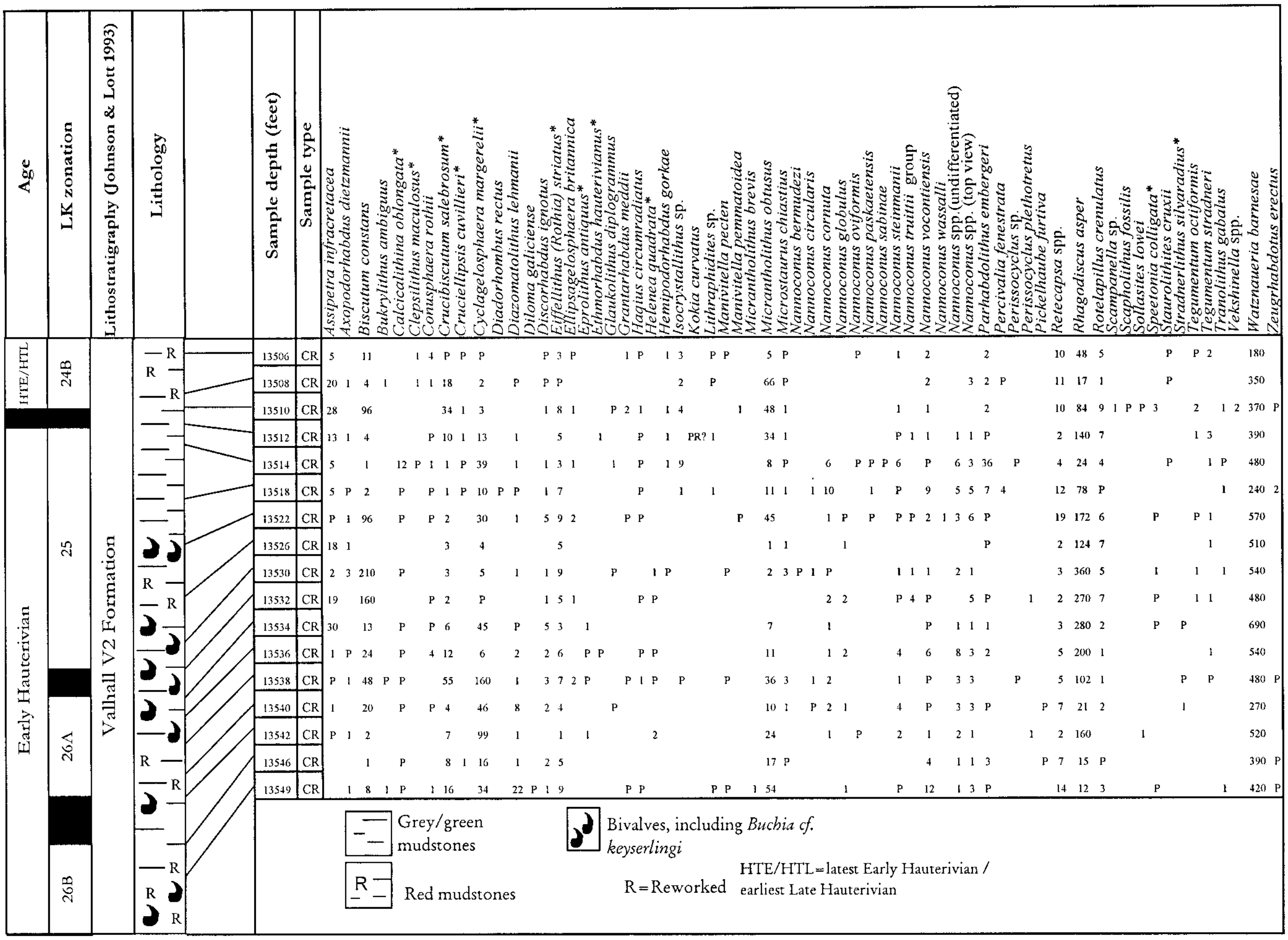


Fig. 20. Stratigraphical distribution of nannofossils from UK Moray Firth Well 15/25a-2 (Early Hauterivian)

Age: Early Hauterivian (lower *amblygonium* MF Zones).
Remarks: the age of this subzone is confirmed in the western Saxony Basin by Well Westerbork-1 [52°46′N 06°36′E] (Adrichem Boogaert & Kouwe, 1993). Here *Endemoceras amblygonium* ammonite-bearing sediments (Rawson, pers. comm., 2000) are identified below the FAD of *Eprolithus antiquus*, a nannofossil confirmed as occurring within upper *amblygonium* ammonite-dated sediments elsewhere in the Saxony Basin (Moorberg exposure; Crux, 1987). A short-lived quantitative incursion of common to abundant *Calculites percernis* (holococcolith sp. 1, Crux, 1987) is also an important correlative event of this subzone within the western Saxony Basin.

Triquetrorhabdulus shetlandensis Zone – LK27

Top: LAD of *Triquetrorhabdulus shetlandensis* [Bown *et al*, 1998].
Base: LAD of *Micrantholithus speetonensis* [Taylor, 1982].
Age: Late Valanginian (unnamed to *Dichotomites* spp. MF Zones).
Remarks: Bown *et al.* (1998) utilized the FAD of *Conusphaera rothii* as a secondary marker for top Valanginian (top BC5). *Conusphaera rothii* does appear absent from the Valanginian of the North Sea but as alluded to by Crux in Bown *et al.* (1998), *C. rothii* is recorded from the Latest Ryazanian (Fig. 22). This zone can be subdivided into two subzones.

Subzone LK27A

Top: LAD of *Triquetrorhabdulus shetlandensis* [Bown *et al.*, 1998].
Base: FAD of *Eiffellithus striatus* [Crux, 1989].
Age: Late Valanginian (unnamed MF Zone).

Subzone LK27B

Top: FAD of *Eiffellithus striatus* [Crux, 1989].
Base: LAD of *Micrantholithus speetonensis* [Taylor, 1982].
Age: Late Valanginian (unnamed to *Dichotomites* spp. MF Zones).

Micrantholithus speetonensis Zone – LK28

Top: LAD of *Micrantholithus speetonensis* [Taylor, 1982].
Base: LAD of common to abundant *Nannoconus oviformis* and common *Kokia curvata/borealis* [this study].
Age: Early Valanginian (*Polyptychites* spp. to *Paratollia* spp. MF Zones).

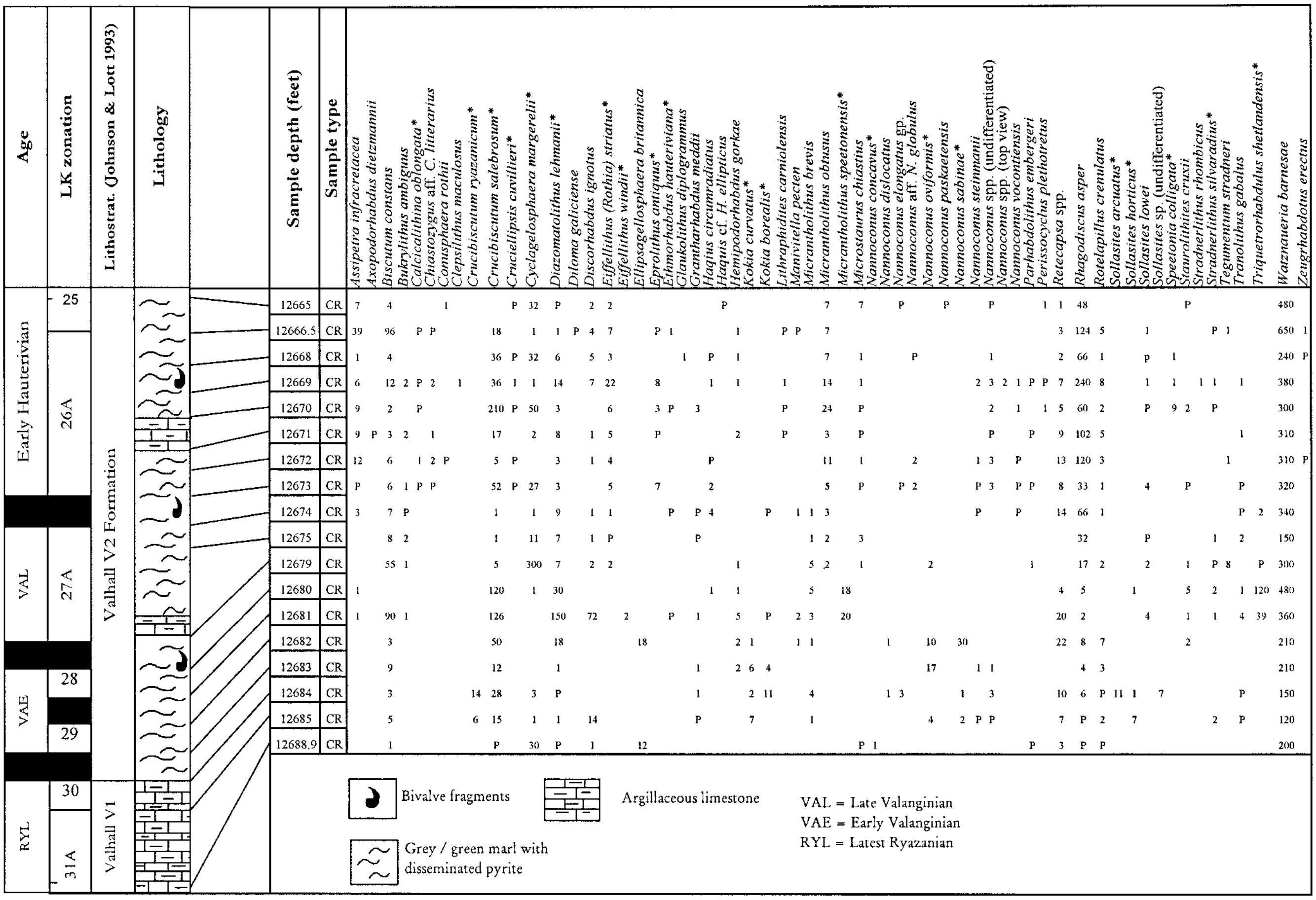


Fig. 21. Stratigraphical distribution of nannofossils from UK Central Graben Well 22/21-4.

Remarks: common *Tranolithus gabalus* is characteristic of the upper part of this zone in the North Sea Basin. Bown *et al.* (1998) subdivided this zone based upon the FAD of *Eiffellithus windii*. This form is generally rare in the Central North Sea and has not been utilized in this study as a reliable correlative datum.

Micrantholithus speetonensis and *Triquetrorhabdulus shetlandensis* are both recorded from the *Platylenticeras* beds (Kemper, 1976, 1992) at the base of the marine Lower Valanginian of the Saxony Basin (equivalent to the *Paratollia* ammonite Zone) in Well Tubbergen-6. A *Platylenticeras* ammonite (species indeterminate) was recovered from the *Platylenticeras* beds in Well Westerbork-1 (Rawson, pers. comm., 2000). Equivalent sediments are described in detail by Kemper (1976, 1992) from nearby exposure at the Suddendorf Quarry, Bad Bentheim, Germany. Here, both *Platylenticeras* spp. and *Paratollia* spp. have been described (Kemper, 1992). The *Platylenticeras* beds at the Suddendorf clay-pit are unfortunately non-calcareous

Nannoconus oviformis Zone – LK29

Top: LAD of common to abundant *Nannoconus oviformis* and common *Kokia curvata/borealis* [this study].
Base: LAD of *Sollasites arcuatus* and/or common *Crucibiscutum ryazanicum* [this study].
Age: earliest Valanginian/latest Ryazanian (lower *Paratollia* spp. to latest *albidum* MF Zones).

Sollasites arcuatus Zone – LK30

Top: LAD of *Sollasites arcuatus* and/or common *Crucibiscutum ryazanicum* [this study].
Base: LAD of *Nannoconus concavus* [this study].
Age: latest Ryazanian (*albidum* MF Zone).
Remarks: *Sollasites arcuatus* can be difficult to differentiate from other *Sollasites* spp. in poorly preserved material. The quantitative influx of *C. ryazanicum* has proven a more reliable datum.

Asymmetrical *Crucibiscutum* sp. also occur within the Upper Hauterivian (Fig. 19), the Middle Albian (*Crucibiscutum* sp. 1 of Jeremiah, 1996) and within the lowermost Cenomanian of onshore UK (e.g. Arlesey section, Bedfordshire).

Micrantholithus brevis Zone – LK31

Top: LAD of *Nannoconus concavus* [this study].
Base: FAD of *Micrantolithus brevis* associated with diverse nannoplankton association [this study].
Age: latest Ryazanian (*albidum* MF Zone).
Remarks: this zone can be subdivided into two subzones.

LKN31A

Top: LAD of *Nannoconus concavus* [this study].
Base: FAD of *Nannoconus concavus* [this study].
Age: latest Ryazanian (*albidum* MF Zone).

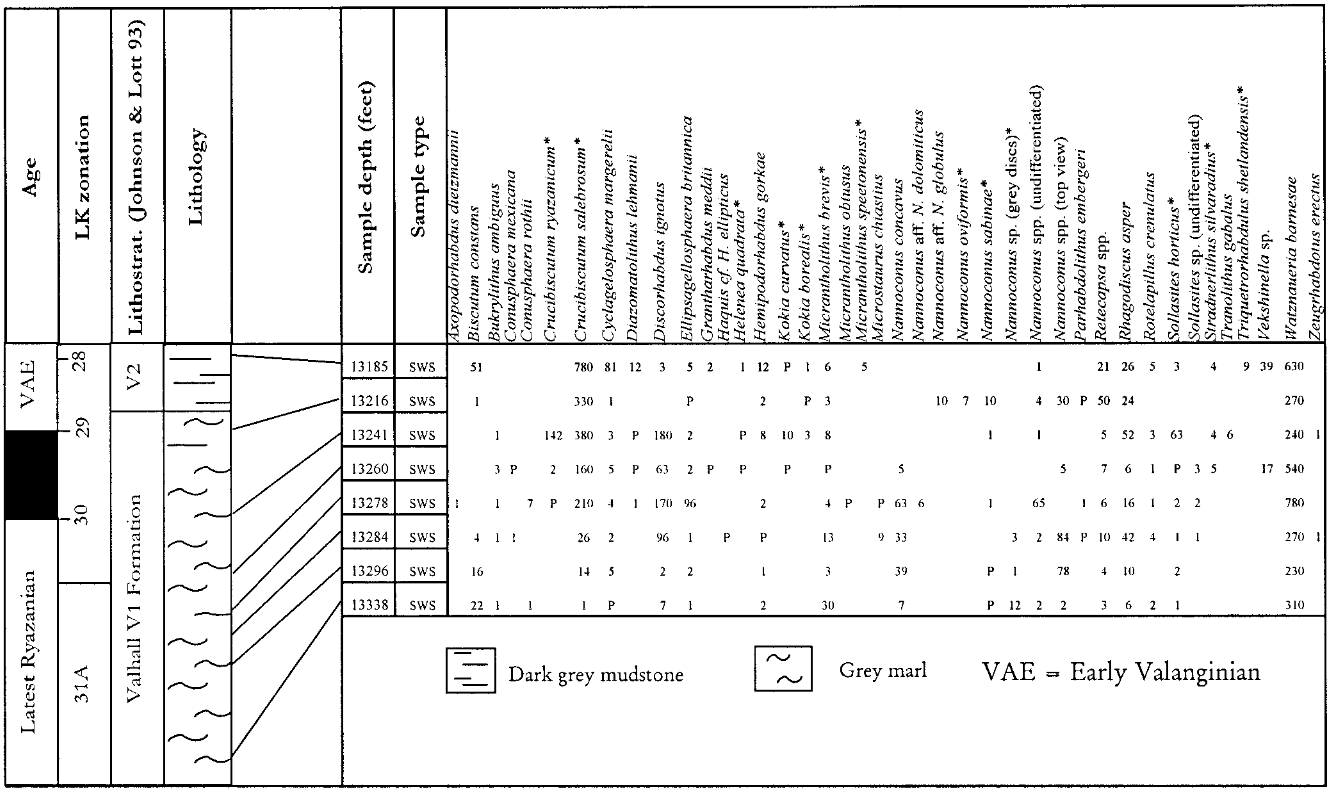


Fig. 22. Stratigraphical distribution of nannofossils from UK Moray Firth Well 21/1b-17.

Remarks: *Sollasites arcuatus*, *Crucibiscutum ryazanicum, Stradnerlithus silvaradius* and *Kokia* spp. have FADs within the upper part of LK31A (Fig. 22). Tethyan connections possibly via a proto-Atlantic Seaway are indicated by the presence of *Conusphaera mexicana* and *Helenea quadrata*. The FAD of common to abundant *Crucibiscutum salebrosum* lies towards the base of this subzone.

LK31B

Top: FAD of *Nannoconus concavus* [this study].
Base: FAD of a diverse nannoplankton association [this study].
Age: Latest Ryazanian (*albidum* MF Zone).
Remarks: the base of this subzone marks a major change in the palaeooceanographic conditions of the North Sea Basin. LKN31B-dated sediments are highly bioturbated exhibiting well oxygenated bottom water conditions. The underlying *albidum* ammonite-dated Kimmeridge Clay sediments are black, laminated and highly organic. In the Central North Sea these sediments are invariably barren of nannofossils. In the Moray Firth sediments containing *stenomphalus* zonal ammonites have yielded an extremely low diversity assemblage composed of *Watznaueria barnesae,* rare *Rhagodiscus asper and Cyclagelosphaera margerelii* (Block 14/26).

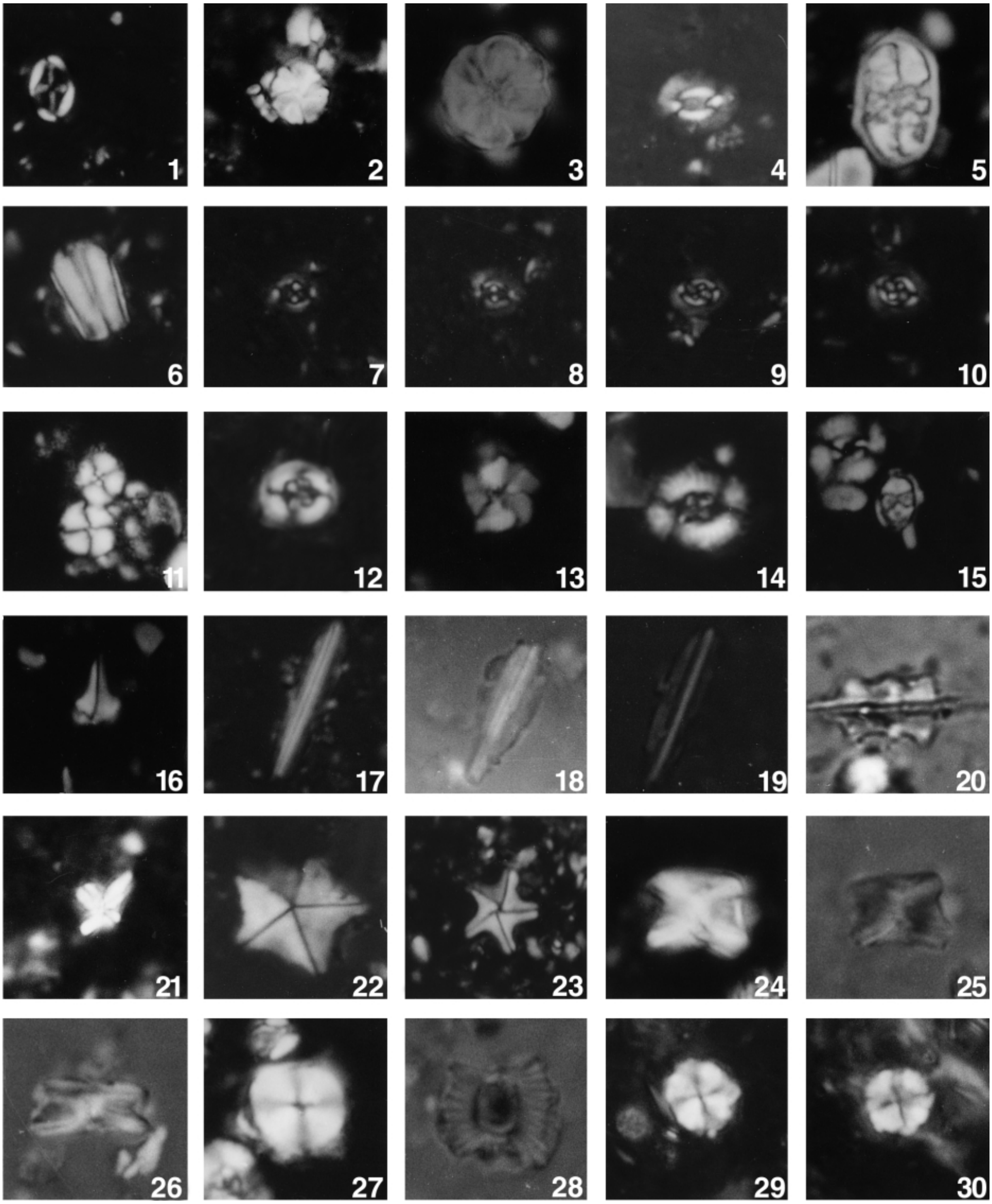
The base of LK31B in a complete section from across this boundary in North Sea well 22/28a-1 (Fig. 1) has shown that this change in nannofossil abundance/diversity is dramatic (unreleased in–house data). The basal 20 cm of calcareous mudstones above *stenomphalus*-dated non-calcareous black, organic claystones yield an opportunistic nannofossil assemblage dominated by *Watznaueria barnesae* and *Micrantholithus brevis* with the remaining nannoflora of low abundance and diversity. *Micrantholithus brevis* constitutes 50–75% of the nannoflora when *W. barnesae* is discounted. Nannoconid abundance rapidly increases above this level together with associated placoliths. *Parhabdolithus embergeri* and *Nannoconus* spp. (grey discs) are characteristic components of this subzone. The base of LK31B is therefore an environmental base. No evolutionary datum can be firmly fixed at this point. Elsewhere in the world (e.g. Yemen) Ryazanian (Berriasian) sediments remain diverse. It would be impractical to use an evolutionary datum from a Tethyan area and apply it to the North Sea when this datum will probably never be seen. It is for this reason that the base of *Retecapsa angustiforata* as used by various authors (Jakubowski, 1987; Bown *et al.*, 1998) is not utilized in this study.

TAXONOMY

A detailed taxonomic section is not provided, although taxa referred to in this paper are listed alphabetically in Appendix A. Taxonomic references not included in the reference list can be found in Bown *et al.* (1998). New species and combinations are detailed below. LMs are uniformly enlarged at ×2300 (1.8 cm=10 μm).

Family **Biscutaceae** Black, 1971
Genus *Biscutum* Black in Black & Barnes, 1959

Biscutum constans cavum ssp. nov.
(Pl. 1, fig. 4)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Derivation of name. Latin *cavum*, meaning hole.
Diagnosis. A large, elliptical *Biscutum* with two monocyclic shields made of petaloid, non-imbricated elements. The distal shield is non-birefringent, whereas the tube cycle and proximal shield are birefringent under cross-polarized light and surround a large central opening. A central cross has not been observed under phase contrast.
Holotype. SMH-18-25 (Pl. 1, fig. 4); sample material is held in the Micropalaeontology Collections at University College London.
Type locality and horizon. Central North Sea, Valhall V4 (Johnson & Lott, 1993), Upper Barremian (Zone LK15).
Dimensions. L: 4.5–6.5 μm (mean length 5 μm), 50 specimens measured.
Remarks. *iscutum constans cavum* together with the smaller *Biscutum constans* quantitatively dominate the low diversity Upper Barremian assemblages of the North Sea area. This Boreal nannofossil assemblage is terminated by the base Aptian transgression and the arrival of cosmopolitan assemblages.

Biscutum constans cavum is characteristic of uppermost Barremian strata from throughout the North Sea Basin.

Genus *Crucibiscutum* Jakubowski, 1986

Crucibiscutum bosunensis sp. nov.
(Pl. 1, figs 7–8)

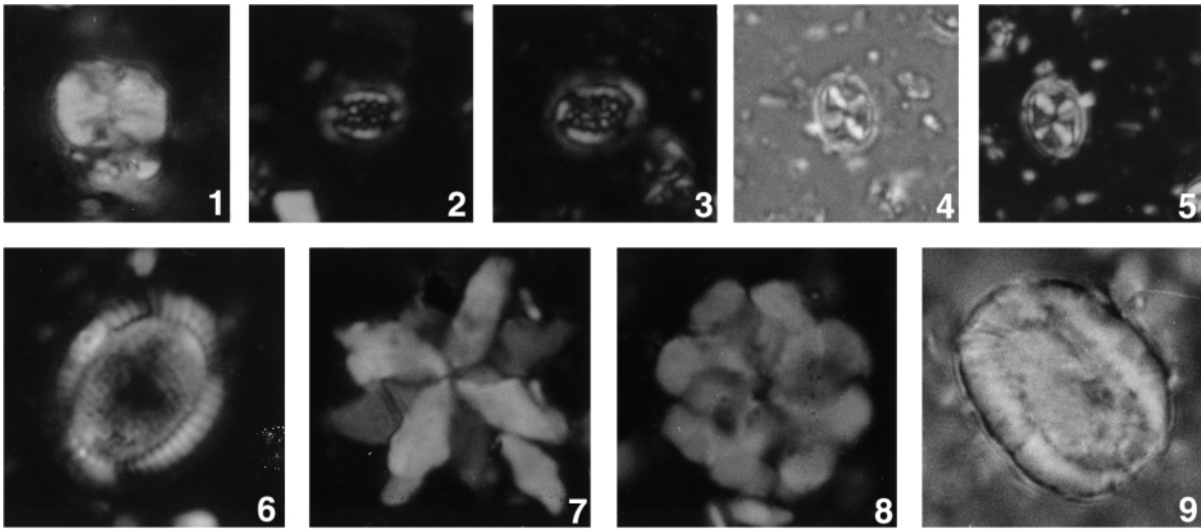
Derivation of name. from the Bosun Field, Outer Moray Firth, North Sea Basin.
Diagnosis. Elliptical placolith with two monocyclic shields and a tube cycle. The distal shield is non-birefringent whereas the tube cycle and proximal shield are birefringent under cross-polarized light. The central cross is axial. Electron microscopy is required to differentiate any fundamental structural differences between *C. bosunensis* and the morphologically similar *C. salebrosum* and *C. hayi*. Under light microscopy the central cross of *C. bosunensis* does appear more bulky than in the more open central area of *C. hayi*. At present, however, other than the large stratigraphical displacement between *C. bosunensis* and *C. salebrosum* it is difficult to differentiate *C. salebrosum* from *C. bosunensis*.
Holotype. SMH-19-22 (Pl. 1, fig. 7); sample material is held in the Micropalaeontology Collections at University College London.
Type locality and horizon. Central North Sea, Valhall V7 (Johnson & Lott, 1993), Upper Aptian.
Dimensions. L: 3.5–5.5 μm (mean length 4.5 μm), 50 specimens measured.
Remarks. An influx of *C. bosunensis* is restricted to the Upper Aptian *nutfieldensis* ammonite Zone in the Central North Sea and is an important correlatable datum. Although morphologically similar to *C. salebrosum* under the light microscope these forms are stratigraphically separated by the Lower Aptian and Barremian.

Crucibiscutum ryazanicum sp. nov.
(Pl. 1, figs 9–10)

Derivation of name. From the Ryazanian stage.
Diagnosis. This *Crucibiscutum* sp. has an asymmetrical central cross.
Holotype. SMH-19-02 (Pl. 1, fig. 9); sample material is held in the Micropalaeontology Collections at University College London.
Type locality and horizon. Central North Sea, Valhall V1 (Johnson & Lott, 1993), uppermost Ryazanian.
Dimensions. L: 4–5 μm (mean length 4.5 μm), 50 specimens measured.
Remarks. An influx of *C. ryazanicum* together with the axially alligned *Crucibiscutum salebrosum* is characteristic of uppermost Ryazanian LK30-dated sediments. *Crucibiscutum* sp. with an asymmetrical cross also occur within the Upper Hauterivian (Fig. 19), the Middle Albian (*Crucibiscutum* sp. 1 of Jeremiah, 1996) and the lowermost Cenomanian of onshore UK (a late evolutionary development from *Crucibiscutum hayi*: e.g. the Arlesey section, Bedfordshire).

Explanation of Plate 1

Fig. 1. *Acaenolithus galloisii*, crossed-nicols, SMH-18-05; 3215 ft (core), UK 13/22a-2, 3215 ft (LK15). **Figs 2–3**. *Assipetra terebrodentarius*: **2**, crossed-nicols, SMH-18-12, 12781 ft (core), UK 15/30-3 (LK9B); **3**, *A. terebrodentarius* (large variety), crossed-nicols, SMH-18-12, 11321.2 ft (core), UK 21/2-6 (LK14B). **Fig. 4**. *Biscutum constans cavum*, (holotype) crossed-nicols, SMH-18-25, 3215 ft (core), UK 13/22a-2 (LK15). **Fig. 5**. *Calcicalithina oblongata*, crossed-nicols, SMH-20-22, 13514 ft (core), UK 15/25a-2 (LK25). **Fig. 6**. *Conusphaera mexicana*, crossed-nicols, SMH-20-10, 13284 ft (core), UK 21/1b-17 (LK31A). **Figs 7–8**. *Crucibiscutum bosunensis*: **7** (holotype) crossed-nicols, SMH-19-22, 3302.4 m (core), UK 21/1a-12 (LK10); **8**, crossed-nicols, SMH-19-20, 3302.4 m (core), UK 21/1a-12 (LK10). **Figs 9–10**. *Crucibiscutum ryazanicum*: **9**, (holotype) crossed-nicols, SMH-19-02, 13241 ft (sws), UK 21/1b-17 (LK30); **10**, crossed-nicols, SMH-19-04, 13241 ft (sws), UK 21/1b-17 (LK30). **Fig. 11**. *Cyclagelosphaera margerelii*, crossed-nicols, SMH-21-10, 11117.5 ft (sws), UK 22/26a-2 (LK14B). **Fig. 12**. *Flabellites oblongus*, crossed-nicols, SMH-20-06, 29.88 m (core), Ashford borehole (RC1544), Kent (LK14B). **Fig. 13**. *Hayesites irregularis*, crossed-nicols, SMH-19-09, 22.5 m (core), Ashford borehole (RC1544), Kent (LK14B). **Fig. 14**. *Helenea quadrata* crossed-nicols, SMH-05-26, 61.32 m (core)–61.4 m (core), BGS borehole 81/43 (LK25). **Figs 15–16**. *Isocrystallithus dispar*: **15**, crossed-nicols, SMH-22-01, *mammillatum* MF Zone, Bed UA3, Speeton, Yorkshire (LK7B); **16**, crossed-nicols (side-view), SMH-22-08, *mammillatum* MF Subzone, Bed UA3, Speeton, Yorkshire (LK7B). **Figs 17–19**. *Lithraphidites houghtonii*: **17**, crossed-nicols, SMH-19-33, 11091 ft (core), UK 22/26a-2 (LK13B); **18** (holotype) bright field, SMH-19-35, 11091 ft (core), UK 22/26a-2 (LK13B); **19**, crossed-nicols, SMH-19-36, 11091 ft (core), UK 22/26a-2(LK13B). **Figs 20–21**. *Lithraphidites moray-firthensis*: **20**, crossed-nicols, SMH-02-22, 890 m (cuttings), Netherlands P/2-2 (LK11A); **21**, crossed-nicols (cross-section), SMH-18-07, 12822 ft (core), UK 15/30-3 (LK11A). **Fig. 22**. *Micrantholithus brevis*, crossed-nicols, SMH-20-24, 15619.6 ft (core), UK 22/28a-1 (LK31B). **Fig. 23**. *Micrantholithus stellatus*, crossed-nicols, SMH-21-34, 11137 ft (sws), UK 22/26a-2 (LK15). **Figs 24–27**. *Nannoconus concavus*: **24**, crossed-nicols, SMH-20-18, 13284 ft (sws), UK 21/1b-17(LK31A); **25**, bright field, same specimen, SMH-20-19; **26**, crossed-nicols, SMH-20-15, 13284 ft (sws), UK 21/1b-17 (LK31A); **27**, crossed-nicols (top-view), SMH-20-14, 13284 ft (sws), UK 21/1b-17 (LK31A). **Fig. 28**. *Nannoconus cornuta*, crossed-nicols, SMH-20-23, 13514 ft (core), UK 15/25a-2 (LK25). **Figs 29–30**. *Nannoconus pseudoseptentrionalis*: **29**, crossed-nicols, SMH-20-04, 29.8 m (core), Ashford borehole (RC1544), Kent (LK14B); **30**, crossed-nicols, SMH-20-28, 30.55 m (core), Ashford borehole (RC1544), Kent (LK14B).



Explanation of Plate 2

Fig. 1. *Nannoconus pseudoseptentrionalis* (side view), crossed-nicols , SMH-19-12, 1580 m (core), Norway 31/3-3 (LK15). **Figs 2–3**. *Seribiscutum dentatum*: **2**, crossed-nicols, SMH-19-14, 9481 ft (sws), UK 21/13b-4 (LK12A); **3** (holotype) crossed-nicols, SMH-19-16, 9481 ft (sws), UK 21/13b-4 (LK12A). **Figs 4–5**. *Staurolithites palmula*: **4**, bright field, SMH-21-21, 1584 m (core), Norway 31/3-3 (LK15); **5** (holotype) crossed-nicols, SMH-21-22, 1584 m (core), Norway 31/3-3 (LK15). **Fig. 6**. *Ethmorhabdus hauteriviana* (wide rim variety), crossed-nicols, SMH-05-33, 63.5 m (core), BGS borehole 81/43 (LK25). **Fig. 7**. *Kokia borealis*, crossed-nicols, SMH-19-28, 12684 ft (core), UK 22/21-4 (LK30). **Fig. 8**. *Kokia curvata*, crossed-nicols, SMH-19-31, 12684 ft (core), UK 22/21-4 (LK30). **Fig. 9**. *Nannoconus oviformis*, crossed-nicols, SMH-18-27, 12683 ft (core), UK 22/21-4 (LK29).

Genus *Seribiscutum* Filewicz *et al.* *in* Wise & Wind, 1977

Seribiscutum dentatum sp. nov.
(Pl. 2, figs 2–3)

Derivation of name. Latin *dentatum*, meaning toothed.

Diagnosis. The central area is covered by 'peg-like' granules. A central cross is not observed.

Holotype. SMH-19-14 (Pl. 2, fig. 4); sample material is held in the Micropalaeontology Collections at University College London.

Type locality and horizon. Central North Sea, Valhall V7 (Johnson & Lott, 1993), lowermost Upper Aptian.

Dimensions Aptian form. L: 6–7 μm (mean length 6.5 μm), 25 specimens measured; Barremian form: L: 3–5 μm (mean length 4.5 μm), 25 specimens measured.

Remarks. The Aptian form of *S. dentatum* has an extremely restricted occurrence within the basal Upper Aptian, intra Zone LK12 (*martinioides* Zone). *Seribiscutum dentatum* reappears downhole in the 'middle' Barremian, Zones LK18/LK19, but at this level is very much smaller than the Aptian form.

Family **Microrhabdulaceae** Deflandre, 1963
Genus *Lithraphidites* Deflandre, 1963

Lithraphidites houghtonii sp. nov.
(Pl. 1, figs 20–22)

Derivation of name. After the Quaternary nannofossil specialist, Dr S. Houghton.

Diagnosis. Calcareous rods with a cruciform cross-section built of long blades of identical optical orientation. This species has a finely serrated blade. The blade may be quite broad but is generally broken to a more slender shape. The blade serrations are not are not as ordered or as coarse as in *Lithraphidites moray-firthensis*.

Holotype. SMH-19-33 (Pl. 1, fig. 20); sample material is held in the Micropalaeontology Collections at University College London.

Type locality and horizon. Central North Sea, Valhall V7 and V6 (Johnson & Lott, 1993), Aptian.

Dimensions. L: 9–12 μm (mean length 11 μm), 50 specimens measured.

Remarks. *L. houghtonii* has two acme occurrences within the Aptian of the North Sea. Its earliest quantitative incursion occurs within the lower part of the Ewaldi Marl (Valhall V6, Johnson & Lott, 1993) whilst a later incursion within the *martinioides* ammonite Zone heralds the evolutionary occurrence of *Lithraphidites moray-firthensis*.

Family **Ahmuellerellaceae** Reinhardt, 1965
Genus *Staurolithites* Caratini, 1963

Staurolithites palmula sp. nov.
(Pl. 2, figs 4–5)

Derivation of name. Latin *palmula*, referring to the blade of an oar.

Diagnosis. Consists of a single zeugoid wall, proximal rim and a central cross without a distal process. The central cross is broad, divided and made of fibrous elements. The central cross is rotated approximately 20 degrees off the principal axes of the ellipse.

Holotype. SMH-21-22 (Pl. 2, fig. 4); sample material is held in the Micropalaeontology Collections at University College London.

Type locality and horizon. Central North Sea, Valhall V4 (Johnson & Lott, 1993), Late Barremian.

Dimensions. L: 4–6 μm (mean length 5 μm), 50 specimens measured.

Remarks. This small *Staurolithites* sp., together with *Biscutum constans cavum* is characteristic of the Boreal Upper Barremian LK15/LK16 dated Valhall V4 and V5 Beds (Johnson & Lott, 1993). *Staurolithites palmula* becomes extremely rare above the basal Aptian transgression but is recorded sporadically as high as the Lower Aptian Ewaldi Marl or Valhall V6.

CONCLUSIONS

Thirty-one zones are presented which have been calibrated to ammonite stratigraphy. These zones are largely a refinement of previous zonations with a particular emphasis on the re-evaluation of the Lower Albian to Upper Barremian. The resultant zonation is based on a large core and field sample dataset from the Central North Sea Basin, onshore UK, Germany and Netherlands. The stratigraphic significance of many Aptian to Upper Barremian markers such as *Lithraphidites moray-firthensis, Farhania varolii, Eprolithus floralis and Nannoconus abundans* has been amended.

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APPENDIX A

Alphabetical list of species considered in this study. Taxonomic references not included in the reference list can be found in Bown *et al.* (1998).

Acaenolithus galloisii Black, 1973

Acaenolithus viriosus Jeremiah, 1996

Assipetra infracretacea (Thierstein, 1973) Roth, 1973

Assipetra terebrodentarius (Applegate *et al.* in Covington & Wise, 1987) Rutledge & Bergen *in* Bergen, 1994

Axopodorhabdus albianus (Black, 1967) Wind and Wise *in* Wise & Wind, 1977

Axopodorhabdus dietzmannii (Reinhardt, 1965) Wind & Wise, 1983

Biscutum constans (Górka, 1957) Black *in* Black & Barnes, 1959

Biscutum constans cavum Jeremiah ssp. nov.

Biscutum dissimilis Wind and Wise *in* Wise & Wind, 1977
Braarudosphaera africana Stradner, 1961
Braarudosphaera batilliformis Troelson & Quadros, 1971
Braarudosphaera primula Black, 1973
Braarudosphaera quinquecostata Hill, 1976
Braarudosphaera regularis Black, 1973
Braarudosphaera stenorhetha Hill, 1976
Braloweria boletiformis (Black, 1972) Crux, 1991
Broinsonia dentata Bukry 1969
Broinsonia enormis (Shumenko, 1968) Manivit, 1971
Bukrylithus ambiguus Black, 1971
Calcicalithina oblongata (Worsley, 1971) Thierstein, 1971
Calculites anfractus (Jakubowski, 1986) Varol & Jakubowski, 1989
Calculites dispar Varol *in* Al-Rifaiy *et al.*, 1990
Ceratolithina bicornuta Perch-Nielsen, 1988
Ceratolithina cruxii Perch-Nielsen, 1988
Ceratolithina hamata Martini, 1967
Chiastozygus litterarius (Gorka, 1957) Manivit, 1971
Clepsilithus maculosus Rutledge & Bown, 1996
Conusphaera mexicana Trejo, 1969
Conusphaera rothii (Thierstein, 1971) Jakubowski, 1986
Corollithion achlyosum (Stover, 1966) Thierstein, 1971
Corollithion exiguum Stradner, 1961
Corollithion rhombicum (Stradner & Adamiker, 1966) Bukry, 1969
Cretarhabdus inaequalis Crux, 1987
Cretarhabdus loriei Gartner, 1968
Crepidolithus burwellensis Black, 1972
Cribrosphaerella ehrenbergii (Arkhangelsky, 1912) Deflandre *in* Piveteau, 1952
Crucibiscutum bosunensis Jeremiah sp. nov.
Crucibiscutum hayi (Black, 1971) Jakubowski, 1986
Crucibiscutum ryazanicum Jeremiah sp. nov.
Crucibiscutum salebrosum (Black, 1971) Jakubowski, 1986
Crucibiscutum sp.1 Jeremiah, 1996
Crucicribrum anglicum Black, 1973
Cruciellipsis cuvillieri (Manivit, 1966) Thierstein, 1971
Cyclagelosphaera margerelii Noel, 1965
Cyclagelosphaera rotaclypeata Bukry, 1969
Cyclagelosphaera shenleyensis Black, 1973
Diadorhombus rectus Worsley, 1971
Diazomatolithus lehmanii Noel, 1965
Diloma primitiva (Worsley, 1971) Wind & Cepek, 1979
Discorhabdus ignotus (Gorka, 1957) Perch-Nielsen, 1968
Eiffellithus monechiae Crux, 1991
Eiffellitus (Rothia) striatus (Black, 1971a) Applegate & Bergen, 1988
Eiffellithus turriseiffelii (Deflandre *in* Deflandre & Fert, 1954) Reinhardt, 1965
Eiffellithus windii Applegate & Bergen, 1988
Ellipsagelosphaera britannica (Stradner, 1963) Perch-Nielsen, 1968
Eprolithus floralis (Stradner, 1962) Stover, 1966
Farhania varolii (Jakubowski, 1986) Varol, 1992
Flabellites oblongus (Bukry, 1969) Crux *in* Crux *et al.*, 1982
Gaarderella granulifera Black, 1973
Gartnerago chiasta Varol, 1991
Gartnerago nanum Thierstein, 1974
Gartnerago praeobliquum Jakubowski, 1986
Gartnerago theta (Black, 1959), Jakubowski, 1986
Glaukolithus diplogrammus (Deflandre *in* Deflandre & Fert, 1954) Reinhardt, 1964
Gorkaea operio Varol and Girgis, 1994
Grantarhabdus coronadventis (Reinhardt, 1966) Grün *in* Grün & Allemann, 1975
Grantharhabdus medii Black, 1971a
Haqius circumradiatus (Stover, 1966) Roth, 1978
Hayesites albiensis Manivit, 1971
Hayesites irregularis (Thierstein *in* Roth & Thierstein, 1972) Covington & Wise, 1987
Helenea quadrata (Worsley, 1971) Rutledge & Bown, 1988
Helicolithus cf. compactus (Bukry, 1969) Varol & Girgis, 1994
Hemipodorhabdus gorkae (Reinhardt, 1969) Grün *in* Grün & Allemann, 1975
Isocrystallithus dispar (Varol *in* Al-Rifaiy *et al.*, 1990) Rawson & Jeremiah, 2001
Kokia borealis Perch-Nielsen, 1988
Kokia curvata Perch-Nielsen, 1988
Laguncula dorotheae Black, 1971
Lithraphidites carniolensis Deflandre, 1963
Lithraphidites houghtonii Jeremiah sp. nov.
Lithraphidites moray-firthensis Jakubowski, 1986
Lordia xenota (Stover, 1966) Varol & Girgis, 1994
Manivitella pecten Black, 1973
Manivitella pemmatoidea (Deflandre *in* Manivit, 1965) Thierstein, 1971
Micrantholithus brevis Jakubowski, 1986
Micrantholithus hoschulzii (Reinhardt, 1966) Thierstein, 1971
Micrantholithus obtusus Stradner, 1963
Micrantholithus speetonensis Perch-Nielsen, 1979
Micrantholithus stellatus Aguado *in* Aguado *et al.*, 1997
Microstaurus chiastius (Worsley, 1971) Grün *in* Grün & Allemann, 1975
Nannoconus abundans Stradner & Grün, 1973
Nannoconus aquitanicus Deres & Achéritéguy, 1980
Nannoconus boletus Deflandre & Deflandre, 1967
Nannoconus borealis Perch-Nielsen, 1979a
Nannoconus bucheri Brönnimann, 1955
Nannoconus circularis Deres & Achéritéguy, 1980
Nannoconus concavus Perch-Nielsen, 1988
Nannoconus cornuta Deres & Achéritéguy, 1980
Nannoconus dolomiticus Cita & Pasquaré, 1959
Nannoconus elongatus Brönnimann, 1955
Nannoconus fragilis Deres & Achéritéguy, 1980
Nannoconus globulus Brönnimann, 1955
Nannoconus grandis Deres & Achéritéguy, 1980
Nannoconus longus Perch-Nielsen, 1988
Nannoconus oviformis Perch-Nielsen, 1988
Nannoconus pseudoseptentrionalis Rutledge & Bown, 1996
Nannoconus steinmannii Kamptner, 1931
Nannoconus truitti Brönnimann, 1955
Nannoconus vocontiensis Deres & Achéritéguy, 1980
Octocyclus magnus Black, 1972
Orastrum perspicuum Varol in Al-Rifaiy *et al.*, 1990
Owenia hilli Crux, 1991
Parhabdolithus embergeri (Noël, 1965) Stradner, 1963
Percivalia fenestrata (Worsley, 1971) Wise, 1983

Perissocyclus tayloriae Crux, 1989
Pickelhaube furtiva (Roth, 1983) Applegate *et al. in* Covington & Wise, 1987
Prediscosphaera columnata (Stover, 1966) Perch-Nielsen, 1984
Prediscosphaera spinosa (Bramlette & Martini, 1964) Gartner, 1968
Radiolithus hollandicus Varol, 1992
Repagulum parvidentatum (Deflandre *in* Deflandre & Fert, 1954) Forchheimer, 1972
Rhagodiscus achlyostaurion (Hill, 1976) Doeven, 1983
Rhagodiscus angustus (Stradner, 1963) Reinhardt, 1971
Rhagodiscus asper (Stradner, 1963) Reinhardt, 1967
Rhagodiscus infinitus (Worsley, 1971) Applegate *et al. in* Covington & Wise, 1987
Rhagodiscus splendens (Deflandre, 1953) Verbeek, 1977
Rotelapillus crenulatus (Stover, 1966) Perch-Nielsen, 1984
Scampanella spp. Forchheimer & Stradner, 1973
Scapholithus fossilis Deflandre *in* Deflandre & Fert, 1954
Seribiscutum dentatum Jeremiah sp. nov.
Seribiscutum primitivum (Thierstein, 1974) Filewicz *et al. in* Wise & Wind, 1977
Sollasites arcuatus Black, 1971a
Sollasites horticus (Stradner *et al. in* Stradner & Adamiker, 1966)
Sollasites lowei (Bukry, 1969) Roth, 1970
Speetonia colligata Black, 1971a
Staurolithites angustus (Stover, 1966) Crux, 1991
Staurolithites crux (Deflandre & Fert, 1954) Caratini, 1963
Staurolithites gausorhethium (Hill, 1966) Varol & Girgis, 1994
Staurolithites glabra (Jeremiah, 1996) Burnett, 1998b
Staurolithites mitcheneri (Applegate & Bergen, 1988) Rutledge & Bown, 1998.
Staurolithites palmula Jeremiah sp. nov.
Stradnerlithus fractus (Black, 1973) Perch-Nielsen, 1984
Stradnerlithus silvaradius (Filewicz *et al. in* Wind & Wise, 1977) Rahmann & Roth, 1991
Tegulalithus tessellatus (Stradner *in* Stradner *et al.*, 1968) Crux, 1986
Tegumentum octiformis (Kothe, 1981) Crux 1989
Tegumentum stradneri Thierstein *in* Roth & Thierstein, 1972
Tetrapodorhabdus decorus (Deflandre *in* Deflandre & Fert, 1954) Wind & Wise *in* Wise & Wind, 1977
Tranolithus gabalus Stover, 1966
Tranolithus phacelosus Stover, 1966
Watznaueria barnesae (Black *in* Black & Barnes, 1959) Perch-Nielsen, 1968
Zeugrhabdotus scutula (Bergen, 1994) Rutledge & Bown, 1996
Zeugrhabdotus sisyphus (Gartner, 1968) Crux, 1989
Zeugrhabdotus noeliae Rood *et al.*, 1971

APPENDIX B

Location	Age/ammonite Zone	LK Zone	Nannofossil association	References
Speeton Cliffs, LA1 Beds	Early Albian *tardefurcata* (*regularis* Subzone)	LK8B	Influx *Repagulum parvidentatum, Tegumentum stradneri* and *Acaenolithus galloisii*; presence of common *Acaenolithus viriosus*	Mitchell & Underwood (1999)
Speeton Cliffs, UB3 Beds	Latest Barremian, *bidentatum*	LK15	Influx *Biscutum constans cavum*, occasional *Staurolithites palmula*, abundant *Manivitella pecten* and presence of *Tegumentum octiformis*	Mitchell & Underwood (1999)
Baulking Quarry, Farringdon, Oxfordshire, UK	Late Aptian, *nutfieldiensis*	LK10	*Crucibiscutum bosunsensis* and *Farhania varolii*	PESGB Newsletter July 1997
Sarstedt, Germany (ME65)	Late Aptian, *nutfieldiensis*	LK10	Abundant *Crucibiscutum bosunensis* and presence of *Farhania varolii*	Below 1982
Sarstedt, Germany (RJD 64)	Late Aptian, *nutfieldiensis*	LK10	Abundant *Crucibiscutum bosunensis*, abundant *Nannoconus globulus* and presence of *Farhania varolii*	Below (1982)
Rothenberg, east of Ochtrup, Germany (ME5) 10 m above ME4	Late Aptian *martinioides* (*T. drewi*)	LK11B	Abundant *Lithraphidites houghtonii*, occasional *Crucibiscutum bosunensis*, *Flabellites oblongus* and common *Prediscosphaera spinosa*	Kemper (1976)
Rothenberg, east of Ochtrup, Germany (ME6) 9 m above ME4	Late Aptian, *martinioides* (*T. drewi*)	LK11B	Abundant *L. houghtonii*, presence of *Crucibiscutum bosunensis*, *Prediscosphaera spinosa* and *Flabellites oblongus*	Kemper (1976)
Rothenberg, east of Ochtrup, Germany (ME4)	Late Aptian, *martinioides* (*T. drewi*)	LK11B	Occasional *Lithraphidites houghtonii*, presence *Prediscosphaera spinosa* and common *Flabellites oblongus*	Kemper (1976)
Rothenberg, east of Ochtrup, Germany (RJD20)	Late Aptian, *martinioides* (*T. drewi*)	LK12	Influx *Lordia xenota*, presence of *oblongus*	Kemper (1976)
Rothenberg, east of Ochtrup, Germany (RJD21)	Late Aptian, *martinioides* (*T. drewi*)	LK12	Influx *Lordia xenota*	Kemper (1976)
Borgers, west of Ochtrup, Germany (ME8)	Latest Early Aptian, *bowerbanki*	LK12	Influx *Lordia xenota*, occasional *Flabellites oblongus* and common *Parhabdolithus embergeri*	Kemper (1976)
Sandwich, Isle of Wight, UK (Atherfield Clay)	Early Aptian, *forbesi*	LK14B	Common *Cyclagelosphaera margerelii* associated with Upper Jurassic reworking (abundant *Ellipsagelosphaera britannica* with *Stephanolithion bigotii bigotii* and *Zeugrhabdotus erectus*)	Ruffell (1992)
Alstatte I, Germany (ME9)	Early Aptian, *Fissicostatus (bodei)*	LK14B	Common *Cyclagelosphaera margerelii* and *Flabellites oblongus*	Kemper (1976)

Table B1. Outcrop locations referred to in the paper with relevant references, ammonite calibration and nannofossil assemblages

APPENDIX C

Depth (m)	Age	LK Zone	Nannofossil association
3.6–3.9 (2 samples)	Latest Early Albian	LK7B	*Isocrystallithus dispar* at 3.6 m. LDO of *Prediscosphaerea columnata* at 3.9 m. FDO of common/abundant *Parhabdolithus embergeri* at 3.9 m
4.35–4.7 (4 samples)	Early Albian	LK8A	FDO *Acaenolithus viriosus* at 4.35 m; presence of *Hayesites albiensis* at 4.6 m and LDO of *Seribiscutum primitivum* at 4.7 m. Samples are non-calcareous and barren of nannofossils below 4.7 m through to 10.85 m
10.85 (1 sample)	Late Aptian	LK12A	*Seribiscutum dentatum* and influx of *Lordia xenota*; presence of common *Crucibiscutum bosunensis*, *Prediscosphaera spinosa* and FDO of *Micrantholithus hoschulzii*
11.1 (1 sample)	Late Aptian	LK12A	*Seribiscutum dentatum* and abundant *Lordia xenota*
11.3–11.65 (2 samples)	Early Aptian	LK13A	Occurrence of *Farhania varolii* at 11.3 m. LDO of *Farhania varolii* at 11.65 m
12.1 (1 sample)	Early Aptian	LK13B	Common *Diazomatolithus lehmanii*, abundant *Stradnerlithus fractus*, common *Nannoconus vocontiensis* and presence of *Eprolithus floralis*. LDO of common/abundant *Repagulum parvidentatum*
12.2–13.95 (9 samples)	Early Aptian	LK14B	FDO of common/abundant *Cyclagelosphaera margerelii* and *Nannoconus pseudoseptentrionalis*. LDO of *Flabellites oblongus* at 13.95 m. Sediments between 13.95 m and 17.3 m are generally non-calcareous. Nannofossil assemblages are non-age diagnostic
17.3–19.6 (9 samples)	Late Barremian	LK15	FDO of common/abundant *Biscutum constans cavum* and common *Staurolithites palmula* at 17.3 m
20.85–22.7 (4 samples)	Late Barremian	LK16	FDO of *Nannoconus abundans* at 20.85 m

Table C1. Heslerton II Borehole, Yorkshire, UK [SE 9199 7589]