

Campanian to Palaeocene biostratigraphy and palaeoenvironments in the Foula Sub-basin, west of the Shetland Islands, UK

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ABSTRACT - For a detailed biostratigraphic framework of the Foula Sub-basin, located west of the Shetland Islands (UK continental shelf), well 205/10-2B is chosen as a reference section. Based on the succession of last occurrence events of nominate taxa, ten stratigraphically distinct Campanian to Palaeocene assemblages are described. The regional applicability of these events is tested by correlation between three wells in the Foula Sub-basin (wells 205/10-2B, 206/3-1 and 206/5-1). Despite some local differences, the biostratigraphy of the Foula Sub-basin compares well with the biostratigraphy of the Western Tethys and the northern North Sea, and is therefore an important link between the southern and northern areas of the Northeast Atlantic margin. A morphogroup analysis of agglutinating foraminifera in well 205/10-2B indicates deposition of Campanian and Maastrichtian mudstones in a well oxygenated, lower bathyal environment, whereas Palaeocene sediments are deposited in a middle to upper bathyal environment. *J. Micropalaeontol.* 19(1): 23–43, May 2000

INTRODUCTION

The Faeroe–Shetland Basin is a deep asymmetric half-graben, situated on the North Atlantic margin, west of the Shetland Islands (Fig. 1). The basin was a major Cretaceous depocentre where thick successions of turbidite-derived mudstones from the Upper Cretaceous Shetland Group accumulated.

The oil industry has shown great interest in the area west of the Shetland Islands due to the discovery of a number of gas and oil fields in the Faeroe–Shetland Basin. As a result, a large number of exploration wells have been drilled in the area, many of which are now released. Despite the need for a good biostratigraphic framework to date the monotonous successions of mudstones of the Upper Cretaceous Shetland Group, no biozonation scheme for the area west of the Shetland Islands has yet been published. However, Ritchie *et al.* (1996) and Knox *et al.* (1997) have described some faunal events found in the area, which may form the basis for a zonation scheme. These events correlate well with those described by King (1989) and King *et al.* (1989) in their zonation schemes for the northern North Sea (Viking Graben and adjacent areas).

Besides the hydrocarbon potential, the Faeroe–Shetland Basin is a very important sea-way linking the North Atlantic and Arctic Oceans. Study of the microfossil assemblages in this basin is important for reconstructing the palaeoceanographic circulation between the North Atlantic and Arctic oceans.

Therefore, the main objective of this study is to define a Campanian – Palaeocene biostratigraphic zonation scheme for a sub-basin of the Faeroe–Shetland Basin, the Foula Sub-basin. In addition to biostratigraphy, the record of microfaunal assemblages is also a useful tool to give insight in the palaeobathymetric and palaeoenvironmental history of the Foula Sub-basin.

Well 205/10-2B is chosen as a reference section for a detailed biostratigraphic framework in the Foula Sub-basin because of the (almost 1070 m) thick succession of Campanian and Maastrichtian sediments present. The biostratigraphy of well

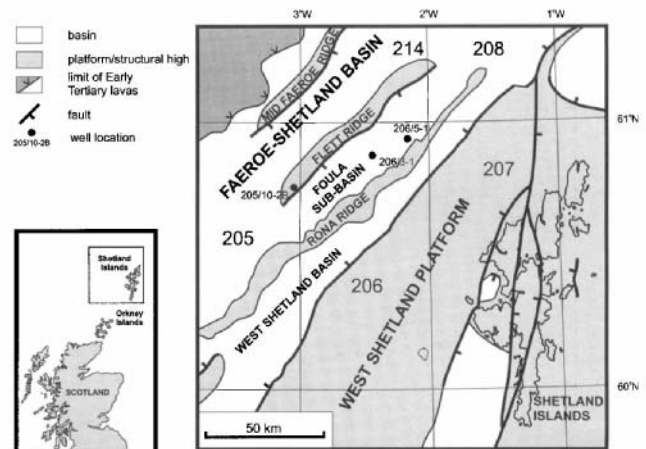


Fig. 1. Location map and detail of Pre-Tertiary structure of the area west of the Shetland Islands (after Ritchie *et al.*, 1996).

205/10-2B is compared with data from two other wells in the Foula Sub-basin: 206/3-1 and 206/5-1 (see Fig. 1 for location).

STUDY AREA

Geological setting

The Faeroe Basin, which was the location of a major Cretaceous depocentre, is a deep asymmetric half-graben between the Rona Ridge and the Mid-Faeroe Ridge (Fig. 1). The graben between the Rona Ridge and the Flett Ridge is referred to as the Foula Sub-basin. The ridges are intrabasinal basement features, blanketed by thick sequences of Cretaceous to Recent sediments. The development of the basin is strongly related to the opening history of the North Atlantic and experienced its major extension during the Cretaceous. Extensive reviews of the basin structural and stratigraphic development have been given by

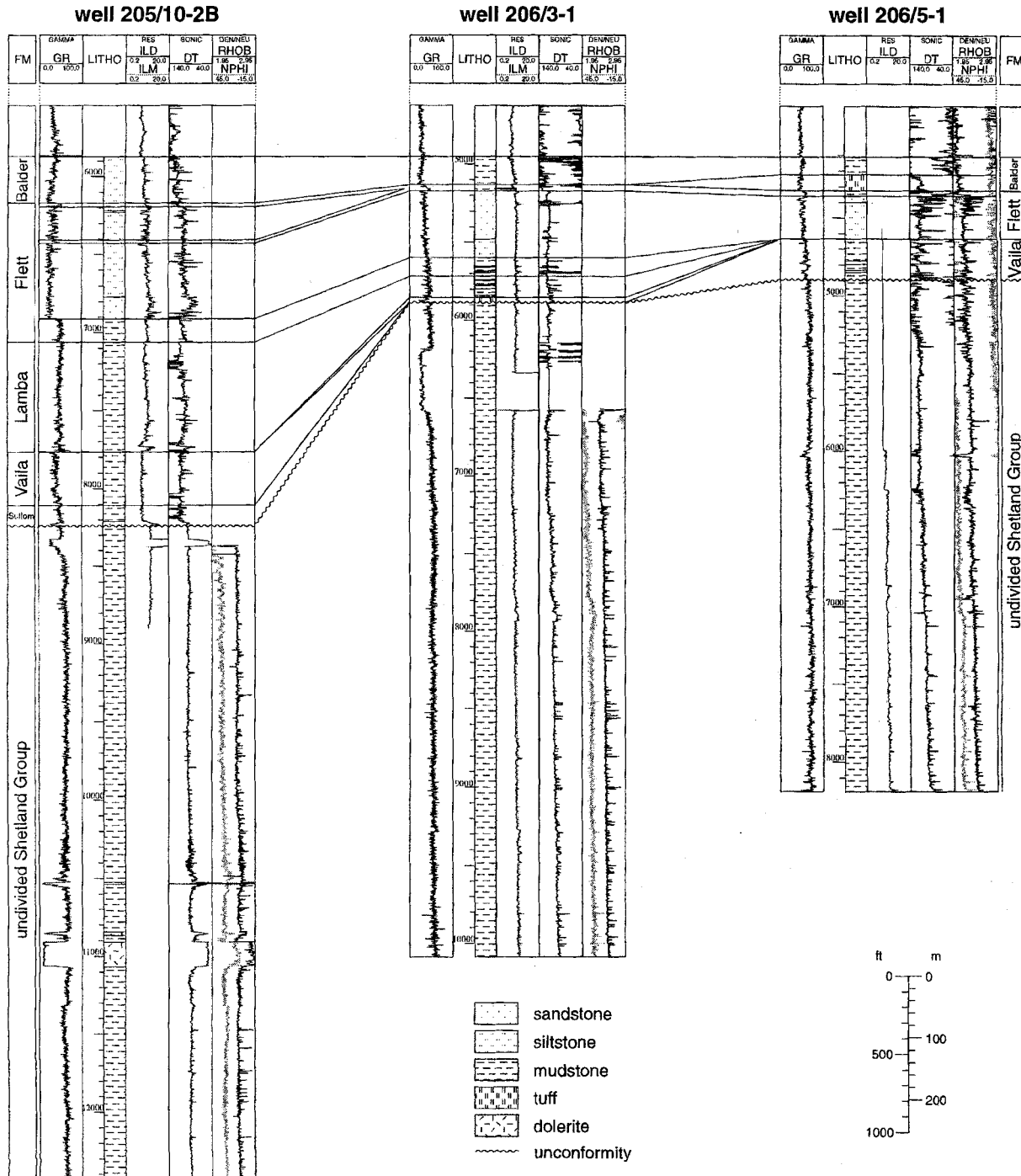


Fig. 2. Lithostratigraphic correlation of three wells in the Foula Sub-basin. Given depths are in feet.

Duindam & van Hoorn (1987), Hitchen & Ritchie (1987), Mudge & Rashid (1987), Earle *et al.* (1989) and Turner & Scrutton (1993), and only a short summary is given here.

Basin development in the Faeroe-Shetland area commenced in Devonian times, although extension was minor. In the West Shetland Basin, sequences of Devonian to Lower Carboniferous

aeolian and fluvial beds occur, hosting the Clair oil field on the Rona Ridge (Ridd, 1981). Uplift and erosion during the Late Carboniferous resulted in widespread erosion. A second cycle of rifting and subsidence occurred during Permian to Early Triassic times, with deposition taking place primarily in continental settings. Pre-rift doming in the Late Triassic to Early Jurassic

period resulted in erosion, before a global marine transgression invaded the area and the first shallow marine sediments of Middle to Late Jurassic age were deposited (Ridd, 1981). Extension continued during the Late Jurassic, although the occurrence of a widespread unconformity at the base of the Cretaceous sequence indicates that basement highs were subjected to uplift and erosion.

The main episode of rifting in the area commenced in Early Cretaceous times with the onset of intensive extension in the Rockall Trough as part of the major North Atlantic sea floor spreading system developing between Greenland and Europe. The Faeroe Basin is regarded as the northern continuation of the Rockall Trough, and its rifting history is strongly related to its opening. The Rockall Trough rift failed in Santonian times (Megson, 1987), leaving the area subjected to thermal subsidence. A distinct pulse of mid-Campanian faulting and associated footwall uplift resulted in a hiatus over the structurally highest parts of the Rona Ridge (Ridd, 1981). Renewed (thermal) extension developed, but was interrupted during the Palaeocene and early Eocene periods by thermal doming associated with the Icelandic mantle plume, which was centred over East Greenland by that time (Ebdon *et al.*, 1995; Nadin *et al.*, 1997). The thermal uplift was accompanied by voluminous subaerial volcanism (Thulean phase) north of the Faeroe Islands (Chalmers *et al.*, 1995); effusive volcanism was succeeded by a final phase of explosive volcanism (Roberts *et al.*, 1984). Due to the regional uplift, extensional faulting developed in the area west of the Shetland Islands, resulting in erosion on the West Shetland margin and deposition of submarine fans in the accelerated subsiding Faeroe Basin. The thermal dome collapsed in the early Eocene with the onset of sea floor spreading between Greenland and Northwest Europe (Roberts *et al.*, 1984; Chalmers *et al.*, 1995). Since this event, the basin has continued to subside.

Lithostratigraphic framework

The Mesozoic and Cenozoic lithostratigraphy of the area west of the Shetland Islands has been recently revised by Ritchie *et al.* (1996) and Knox *et al.* (1997). Based on well log character and transitions, formations are differentiated in the Shetland Group (Kyrre, Jorsalfare and Sullom Formations), Faeroe Group (Vaila and Lamba Formations) and the Moray Group (Flett and Balder Formations). The Shetland Group is a succession of pale grey to dark grey calcareous and non-calcareous mudstones and is laterally equivalent to the Chalk Group in the Central and Southern North Sea. In the Foula Sub-basin, it is difficult to identify formation boundaries in the monotonous succession of Campanian and Maastrichtian mudstones, and therefore the Shetland Group is undivided (see Fig. 2).

The Maastrichtian calcareous mudstones are unconformably overlain by sediments of the Sullom Formation (lower Palaeocene), Vaila Formation and Kettle Member of the Lamba Formation (upper Palaeocene) (see Fig. 2). This basal Palaeocene unconformity is indicated by a downhole increase in gamma-ray values and decrease in velocity. Due to thermally induced uplift in the early Palaeocene (Ebdon *et al.*, 1995; Nadin *et al.*, 1997), the area was subjected to erosion, resulting in a stratigraphic gap encompassing the uppermost Maastrichtian and Lower to Upper Palaeocene sediments. In well 205/10-2B

the Maastrichtian sediments are overlain by calcareous mudstones of the Sullom Formation, deposited during late early Palaeocene times. The upper boundary of the Sullom Formation with the silty calcareous mudstones of the Vaila Formation (Upper Palaeocene) is taken at a downhole increase in the gamma-ray response. The presence of the lower unit of the Vaila Formation (V1) in well 205/10-2B is indicated by the recovery of abundant *Cenosphaera lenticularis* (Grzybowski, 1896) at 8060 feet (2457 m), just above the upper boundary of the Sullom Formation (Ritchie *et al.*, 1996). The medium to dark grey silty calcareous mudstones of the Vaila Formation are characterized by relatively low gamma-ray values. In more basinal sections, the Vaila Formation contains thick sandstone units; however, in well 206/5-1 only thin sandstone layers are present.

In places where the tuffaceous siltstones of the Kettle Member in the base of the Lamba Formation are absent (characterized by low gamma-ray values and a high velocity; see well 206/3-1 in Fig. 2), the upper boundary of the Vaila Formation with the light to medium grey mudstones of the Lamba Formation is distinctive by the downhole increase in gamma-ray values. In well 206/5-1 the Lamba Formation is absent and the Flett Formation rests unconformably on the Vaila Formation. The distinction between the variegated sediments of the Flett Formation and the more uniform mudstones of the Lamba Formation is not very well defined, and is taken here at a downhole increase in gamma-ray response. In the Flett Formation two sandstone members are recognized: a thick and geographically widespread unit of Upper Colsay sandstones and, on top of that, separated by a persistent layer of mudstones, the more restricted Hildasay sandstones. Both units are dominated by progradational and aggradational shallow marine mudstones and sandstones. The top of the Flett Formation is marked by a downhole increase in gamma-ray values, indicating the change from silty mudstones rich in tuff (from the Balder Formation) to darker grey mudstones containing fewer tuffs. The tuffs of the Balder Formation are believed to have been derived from the late phase of the Thulean volcanism in the Greenland–Faeroe area (Chalmers *et al.*, 1995) and are of early Eocene age (Earle *et al.*, 1989). The upper boundary of the Balder Formation is identified by a downhole decrease in gamma-ray values and increasing velocity. The tuff is not recorded in every well, because it is masked by the normal terrigenous sedimentation.

The deepening of the basin towards well 205/10-2B is evident from the thickness of the Palaeocene sedimentary successions in the three wells and from seismic data (Mudge & Rashid, 1987), indicating that the depocentre of the Palaeocene Faeroe–Shetland Basin was located NW of the Foula Sub-basin.

MATERIAL AND METHODS

Ditch cutting samples from the three studied wells were provided by the Department of Trade and Industry (DTI) Core Facility in Edinburgh. The reference well 205/10-2B was drilled in 1984 at 60°5'43.235"N and 03°03'21.812"W in 447.5 m of water, with Britoil plc as the operator. Well 206/3-1 (Amoco, UK) was also drilled during 1984 at 60°52'42.092"N and 02°26'23.734"W in a water depth of 290.8 m, while well 206/5-1 (Shell, UK) was drilled during 1976 at 60°50'25.98"N and 02°10'14.26"W in a

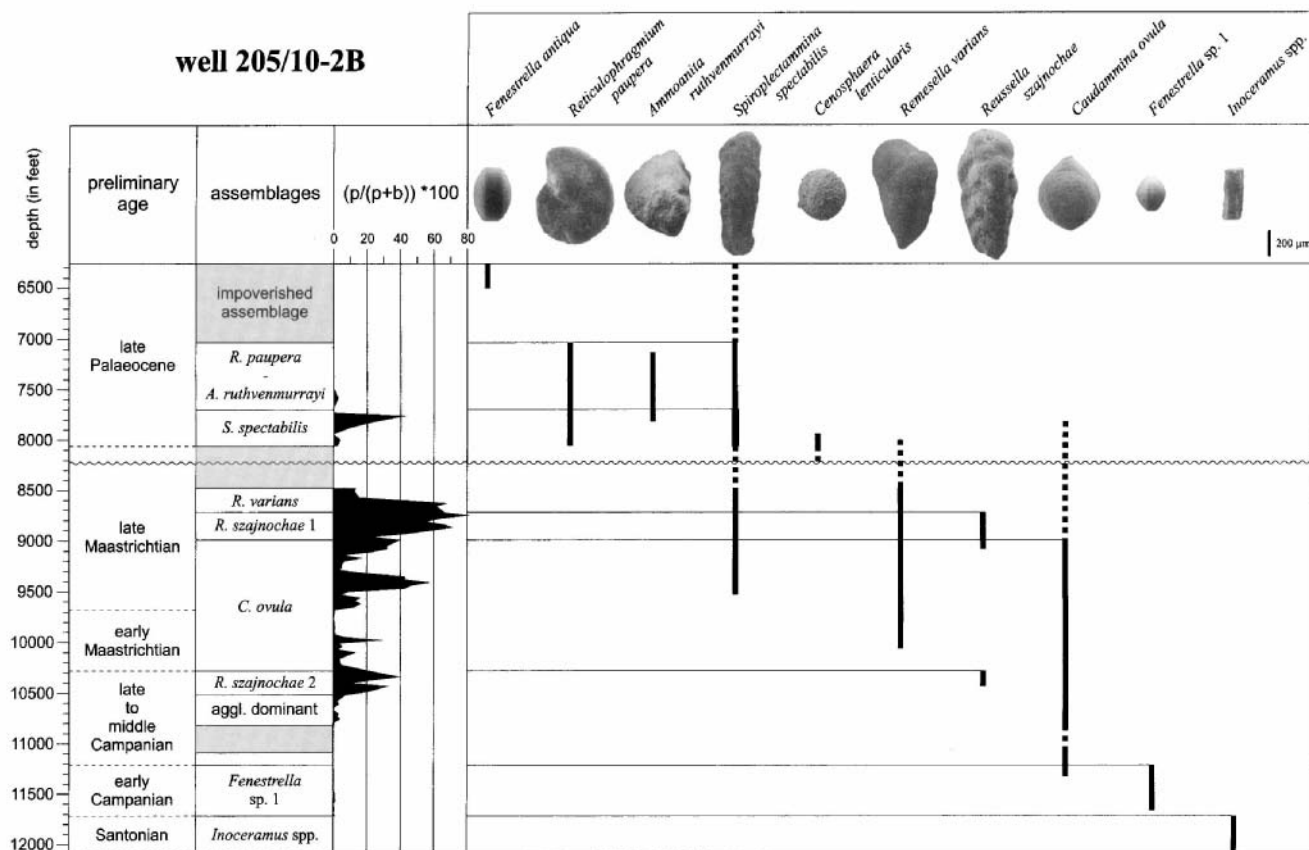


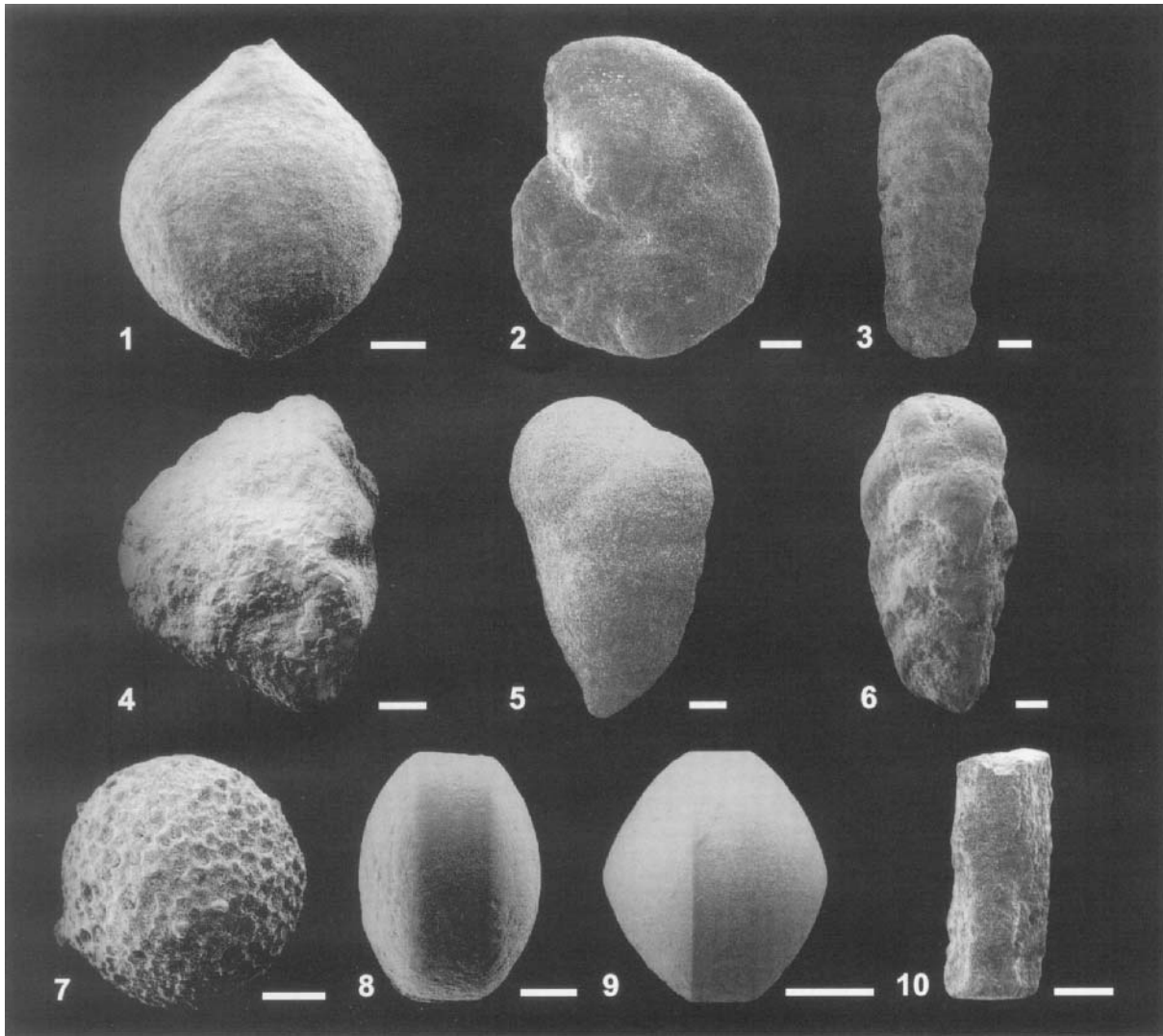
Fig. 3. Chronostratigraphy and distribution of index taxa in well 205/10-2B.

water depth of 284.4 m. All depths of the samples are reported in feet below rotary kelly bushing (which is 1540 feet (469 m) above the seabed for well 205/10-2B, whereas it is 1044 feet (318 m) and 1018 feet (310 m) for wells 206/3-1 and 206/5-1 respectively). The samples, ranging in dry weight from 33 to 77 g, were disintegrated in boiling sodium carbonate solution and washed over a 63 µm sieve. Foraminifera, radiolarians and diatoms were picked from the > 125 µm fraction and mounted on cardboard slides. Altogether, 124 samples of well 205/10-2B were examined, most of them spaced at a 30 feet (9.1 m) interval. Because an 18³/₈ inches (476 mm) casing is placed at a depth of 8349 feet (2545 m), no samples were available for the interval near the casing (8060–8420 feet, 2457–2566 m). Due to the occurrence of dolerite dykes in the lower part of the studied section, samples from 10280–11060 feet (3133–3371 m) are excluded from the analysis. In the samples a total of 153 agglutinating species (including taxa in open nomenclature) were recognized (see Appendix). Estimating the abundance of agglutinating foraminifera is complicated by the fact that many tubular and uniserial rectilinear taxa are recovered only as fragments. Therefore, to describe the faunal assemblages as accurately as possible, every specimen and all identifiable fragments (including calcareous benthic and planktonic taxa for consistency) were counted, although this might result in some duplication. The distribution of the microfossils in well 205/10-2B is given in order of first downhole appearance in the Appendix.

RESULTS

Microfossil assemblages

The Campanian–Palaeocene succession of benthic and planktonic foraminifera, diatoms and radiolarians in well 205/10-2B can be subdivided into ten stratigraphically distinct assemblages, mainly based on the last uphole occurrence events of stratigraphically important agglutinated species (see Fig. 3 and Plate 1) and abundances of other dominant taxa. The chronostratigraphy is based on events reported from the northern North Sea (King, 1989; King *et al.*, 1989; Mudge & Copestake, 1992; Gradstein *et al.*, 1994; Gradstein & Bäckström, 1996), the area west of the Shetland Islands (Ritchie *et al.*, 1996; Knox *et al.*, 1997) and from the Norwegian margin (Gradstein, personal observations). In addition to the stratigraphically important taxa, the tubular taxa (*Rhabdammina* spp. and *Rhizammina* spp.) are dominant throughout the studied section. Furthermore, Palaeocene assemblages are characterized by abundant *Haplophragmoides* spp., trochamminids, *Karrerulina* spp., *Criboströmoides* spp. and *Recurvoides* spp. Throughout the Campanian and Maastrichtian, *Psammospaera* spp. and *Saccamina* spp. are abundant, with common calcareous benthic and planktonic foraminifera down to a depth of 10520 feet (3206 m). Pyritised moulds of diatoms and radiolarians are common throughout the studied section, while the Lower Campanian is characterized by high abundances of them. Only last uphole occurrence (LO) events are reliable, as we are dealing with ditch cuttings in this



Explanation of Plate 1.

Stratigraphically important microfossils from well 205/10-2B. Horizontal bar is 100 μm . **fig. 1.** *Caudammina ovula* (Grzybowski), 9800 ft (2987 m), $\times 414$. **fig. 2.** *Reticulophragmium pauperum* (Chapman), 7220 ft (2201 m), $\times 319$. **fig. 3.** *Spiroplectammina spectabilis* (Grzybowski), 7310 ft (2228 m), $\times 250$. **fig. 4.** *Ammonoanita ruthvenmurrayi* (Cushman & Renz), 7220 ft (2201 m), $\times 366$. **fig. 5.** *Remesella varians* (Glaessner), 10040 ft (3060 m), $\times 291$. **fig. 6.** *Reussella szajnochae* (Grzybowski), 8930 ft (2722 m), $\times 241$. **fig. 7.** *Cenosphaera lenticularis* (Grzybowski), 8060 ft (2457 m), $\times 491$. **fig. 8.** *Fenestrella antiqua* (Grunow), 6290 ft (1917 m), $\times 449$. **fig. 9.** *Fenestrella* sp. 1, 9770 ft (2978 m), $\times 678$. **fig. 10.** *Inoceramus* spp. needle, 11 720 ft (3572 m), $\times 466$.

study; therefore, the succession of assemblages will be discussed in order from youngest to oldest.

1. Impoverished assemblage

Interval: 6260–7100 feet (1908–2164 m)

Age: latest part of late Palaeocene

Samples examined from this interval were almost barren of foraminifera. This interval spanned a period with locally high input of terrigenous material which has significantly reduced the faunal record in the sediments. Sparse occurrences of *Spiroplectammina spectabilis* (Grzybowski, 1898), *Rhabdammina robusta* (Grzybowski, 1898) and *Reticulophragmium* sp. aff. *amplectens* (Grzybowski, 1898) are recorded, with abundant small reticulate *Cenosphaera* spp. In the top samples of this

interval, a few large, pillbox shaped pyritized moulds of the diatom *Fenestrella antiqua* (Grunow, 1882) are recorded. High abundances of these diatoms are characteristic of the lower Eocene Balder Formation (King, 1989; Gradstein *et al.*, 1994; Mudge & Bujak, 1996; Knox *et al.*, 1997). Therefore, the low abundance of this diatom in this interval, combined with the lithology characteristics, indicates a late Palaeocene age.

2. *Reticulophragmium pauperum*–*Ammonoanita ruthvenmurrayi* assemblage

Interval: 7100–7700 feet (2164–2347 m)

Age: middle part of late Palaeocene

The last uphole occurrences (LOs) of many taxa are observed

near the top of this interval, including that of *Reticulophragmium paupera* (Chapman, 1904), *Ammoanita ruthvenmurrayi* (Cushman & Renz, 1946) and the last common occurrence (LCO) of *Spiroplectammina spectabilis* (see Fig. 3 and Appendix). In the northern North Sea, the LOs of these taxa mark the 'T. ruthvenmurrayi–R. paupera' Zone of Gradstein *et al.* (1988), which is equivalent to Zone NSA1b of King (1989). In the RASC zonal model of Gradstein & Bäckström (1996), this interval correlates with Zone NSR2 (late Palaeocene). In the area west of the Shetland Islands, Knox *et al.* (1997) report in the top of the Lamba Formation (Upper Palaeocene) the LO of a low diversity fauna with *S. spectabilis*. Stratigraphically just below this event, they report a high-diversity agglutinating fauna, which might correlate with the extremely abundant (more than 30 specimens per studied gram) and diverse interval observed in well 205/10-2B (7130–7220 feet, 2173–2201 m). The assemblage also contains common *Rhabdammina* spp., *Rhizammina* spp., *Haplophragmoides* spp., *Karrerulina* spp., *Glomospira* spp., *Trochammina* spp., *Budashevaella multicamerata* (Voloshinova & Budasheva, 1961), *Cribrostomoides* spp. and *Recurvoides* spp.

3. *Spiroplectammina spectabilis* assemblage

Interval: 7700–8060 feet (2347–2457 m)

Age: early part of late Palaeocene

The last abundant occurrence (LAO) of *Spiroplectammina spectabilis* marks the top boundary of this interval. This event should not be confused with the high-abundance and high-diversity event in the previous interval where *S. spectabilis* is also fairly common, although in lower relative proportions (typically less than 4% of the total fauna). The *S. spectabilis* assemblage is characterized by a less diverse and less abundant foraminiferal fauna (less than seven specimens per gram) with high relative proportions of *S. spectabilis* (7–20% of the total fauna) and common *Rhabdammina* spp., *Rhizammina* spp., *Haplophragmoides* spp., *Karrerulina* spp., *Glomospira* spp., *Trochammina* spp., *B. multicamerata*, *Cribrostomoides* spp., *Recurvoides* spp. and *R. paupera*. This interval correlates with Zone NSA1a of King (1989). High abundances of *S. spectabilis* are also recorded from the middle part of the Upper Palaeocene of the western Barents Sea by Nagy *et al.* (1997). Large reticulate spherical radiolarians, *Cenosphaera lenticularis*, occur in the base of this interval. These are reported from the lower part of the upper Palaeocene sediments in the North Sea (Jones, 1988; Zone NSP2 of King, 1989; Mudge & Copestake, 1992; Unit 1 of the Vaila Formation, Knox *et al.*, 1997). In this interval reworked Late Cretaceous planktonic foraminifera also occur in well 205/10-2B. However, the observation of *Parasubbotina pseudobulloides* (Plummer, 1927) and *Subbotina triloculinooides* (Plummer, 1926) confirms the Palaeocene age of this interval (Toumarkine & Luterbacher, 1985; Berggren & Norris, 1997).

4. *Remesella varians* assemblage

Interval: 8480–8720 feet (2585–2658 m)

Age: late Maastrichtian

A distinct change in the composition of the faunal assemblages is observed across the Palaeocene/Cretaceous unconformity (at

8223 feet, 2506 m). The assemblage now consists mainly of *Rhabdammina* spp., *Rhizammina* spp., *Saccammina* spp., *Psammosphaera* spp., calcareous benthic and planktonic species. The common to abundant planktonic taxa include *Heterohelix globulosa* (Ehrenberg, 1840), *Heterohelix planata* (Cushman, 1938), *Laeviheterohelix dentata* (Stenestad, 1968), *Laeviheterohelix glabrans* (Cushman, 1938), *Globigerinelloides volutus* (White, 1928), *Globotruncanella petaloidea* (Gandolfi, 1955), *Archaeoglobigerina blowi* (Pessagno, 1967), and *Hedbergella holmdelensis* (Olsson, 1964). The consistent occurrence of *Remesella varians* (Glaessner, 1937) below the unconformity makes it the nominate taxon of this interval. Because of the absence of *Pseudotextularia elegans* (Rzehak, 1891) in this assemblage, this interval probably correlates best with the FCN21a Zone of King *et al.* (1989). In the Northeast Atlantic, the *R. varians* Zone is a useful indicator for the late Maastrichtian (Kuhnt *et al.*, 1992; Kuhnt & Kaminski, 1997).

5. *Reussella szajnochae* 1 assemblage

Interval: 8720–8990 feet (2658–2740 m)

Age: late Maastrichtian

This interval is confined between the LO event of *Reussella szajnochae* (Grzybowski, 1896) and LCO event of *Caudammina ovula* (Grzybowski, 1896). It is distinguished from the interval above by the occurrences of both *R. varians* and *R. szajnochae*. The microfauna is dominated by abundant planktonic foraminifera, of which the main contributors are *H. globulosa*, *G. volutus* and *Archaeoglobigerina* spp. The assemblage also contains common *Rhabdammina* spp., *Rhizammina* spp., *Saccammina* spp., *Psammosphaera* spp., and calcareous benthic and planktonic species. The LO of the calcareous benthic species *R. szajnochae* is reported from the late Maastrichtian (Zone FCN20d of King *et al.*, 1989; Ritchie *et al.*, 1996). This late Maastrichtian age is confirmed by the occurrence of *Abathomphalus mayaroensis* (Bolli, 1951) in this interval (Caron, 1985; King *et al.*, 1989).

6. *Caudammina ovula* assemblage

Interval: 8990–10280 feet (2740–3133 m)

Age: early–late Maastrichtian

This assemblage is characterized by the presence of *Caudammina ovula*. Most of the specimens in the studied samples are assigned to *C. ovula*, rather than to the larger species known as *C. gigantea* (Geroch, 1960). In this interval a four-fold subdivision can be made based on the abundance of calcareous benthic and planktonic foraminifera. The record of calcareous benthic foraminifera shows the same trend in abundances as the planktonic foraminiferal record. Therefore, the peaks in the (p/(p+b))-ratios indicate intervals with abundant calcareous benthic and planktonic foraminifera (Fig. 3).

In the upper part of this interval planktonic foraminifera are still abundant (dominated by *H. globulosa* and *G. volutus*). However, between 9110 feet (2777 m) and 9290 feet (2832 m) the calcareous benthic and planktonic foraminifera are less abundant and the interval is characterized by *Rhabdammina* spp., *Rhizammina* spp., *Saccammina* spp., *Psammosphaera* spp., *R. varians* and *C. ovula*.

At 9290 feet (2832m) there is a downhole change in assemblage composition to dominantly calcareous foraminifera again, with abundant *H. globulosa*, *G. volutus* and *Archaeoglobigerina* spp.

In the lower part of the interval (9680–10 200 feet, 2950–3109m) calcareous foraminifera are less abundant again. Besides the common *Rhabdammina* spp., *Rhizammina* spp., *Saccammina* spp., *Psammospaera* spp. and *Recurvoides* spp., the assemblage is characterized by *C. ovula*, and the *Karrerulina*/*Gerochammina* spp. group. In the northern North Sea and west of the Shetland Islands, the break between calcareous species above and non-calcareous forms below, is correlated with the Lower/Upper Maastrichtian boundary (upper boundary of Zone FCN20a of King *et al.*, 1989; Ritchie *et al.*, 1996).

7. *Reussella szajnochae* 2 assemblage

Interval: 10 280–10 520 feet (3133–3206 m)

Age: late Campanian

The upper boundary of this interval is marked by the downhole shift to abundant calcareous foraminifera and the downhole re-appearance of *Reussella szajnochae*. The planktonic foraminifera are dominated by *G. volutus* and *Archaeoglobigerina* spp. The LO event of *R. szajnochae* 2 is reported to mark the Campanian/Maastrichtian boundary (top of Zone FCN19 of King *et al.*, 1989; Ritchie *et al.*, 1996).

8. Agglutinated foraminifera dominated assemblage

Interval: 10 520–11 210 feet (3206–3417 m)

Age: mid-Campanian

The top of this interval is characterized by a downhole change to a dominantly agglutinating fauna. In this interval the recovered assemblage consists only of long-ranging taxa, with common *Rhabdammina* spp., *Rhizammina* spp., *Saccammina* spp., *Psammospaera* spp., *Recurvoides* spp. and *C. ovula*. In the lowest part of the interval pyritized moulds of radiolarians and diatoms become more abundant. The influx of a characteristic conical shaped diatom infilling (*Fenestrella* sp. 1) marks the lower boundary of this interval.

9. *Fenestrella* sp. 1 assemblage

Interval: 11 210–11 720 feet (3417–3572 m)

Age: early Campanian

The influx of pyritised moulds of *Fenestrella* sp. 1 characterizes this interval, which is accompanied by very abundant pyritized infillings of other diatom species and radiolarians (pyritized and non-pyritized). The lower boundary of this interval (Santonian/Campanian boundary) is indicated by the LCO of characteristic shell fragments of *Inoceramus* spp. An alternative marker for this event is the influx of large, non-pyritized, spherical radiolarians. The occurrence of *Fenestrella* sp. 1 is also recognized in the Haltenbanken area of the Norwegian margin (Gradstein, personal observations). King *et al.* (1989) and Ritchie *et al.* (1996) did not separate the last two assemblages: the *Fenestrella* sp. 1 assemblage was incorporated in their Lower Campanian interval of dominantly non-calcareous foraminifera (FCN18).

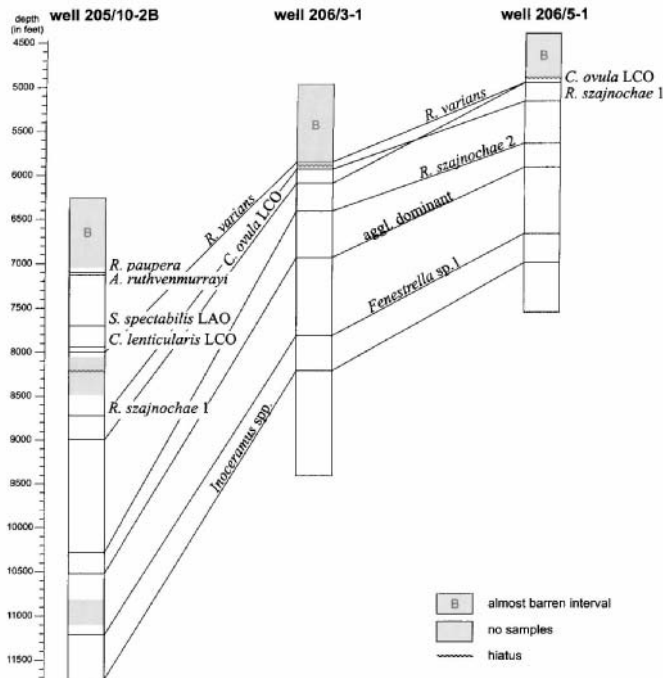


Fig. 4. Biostratigraphic correlation of last occurrences and last common occurrences (LCO) of nominate taxa in three studied wells in the Foula Sub-basin.

10. *Inoceramus* spp. assemblage

Sample: 11 720 feet (3572 m)

Age: Santonian

Little information is available for this Santonian assemblage, as only the lowermost studied sample contains common inoceramid prisms. The biosiliceous microfossils (diatoms and radiolarians) are still very abundant in this sample.

Biostratigraphic correlation

To test the regional applicability of the biostratigraphic events described from well 205/10-2B, a correlation between the last occurrence events of the nominate taxa observed in the three studied wells is shown in Fig. 4. Only last occurrence (LO) and last common occurrence (LCO) events are considered here, because we are dealing with ditch cutting samples in this study. In the situations where events occur close to the erosional upper boundary of the Shetland Group, the true extinction level of these taxa might have been eroded during the early Palaeocene erosional event. Consequently, the observed last occurrence of a taxon might not be correlative to its true stratigraphic extinction level. Unfortunately, the Palaeocene samples of wells 206/3-1 and 206/5-1 are almost barren of microfossils; therefore, in the discussion we concentrate on the Campanian–Maastrichtian events of the Shetland Group.

All events described from well 205/10-2B are recognized in the other wells. In all three wells the LO of *R. varians* was observed close to the erosional upper boundary of the Shetland Group, which suggests that the true LO level of this species might have been eroded during the basal Palaeocene erosional event. The same holds true for the LCO event of *C. ovula* in well 206/5-1.

AGE (my)	STANDARD STAGE		Western Tethys Zonation of Kuhnt <i>et al.</i> (1992)	Zumaya Zonation of Kuhnt & Kaminski (1997)	Faunal assemblages of Foula Basin, this study	northern North Sea Zonation of King (1989) and King <i>et al.</i> (1989)		
	PALEOCENE	THANETIAN				2	<i>Verneulinoides subeoceanus</i>	
55	LATE	THANETIAN	not studied	<i>Spiroplectammina spectabilis</i>	impoverished assemblage	b	<i>Trochammina ruthvenmurrayi</i>	
		SELANDIAN			1			a
60	EARLY	DANIAN	<i>Spiroplectammina spectabilis</i>	unnamed	hiatus	NSA		
					FCN			
65	LATE	MAASTRICHTIAN	<i>Remesella varians</i>	<i>Remesella varians</i>	<i>Remesella varians</i>	21	b	<i>P. elegans</i>
					<i>Reussella szajnochae</i> 1		a	<i>Rugoglobigerina</i> spp.
70	MIDDLE	EARLY	<i>Caudammina gigantea</i>	<i>Caudammina ovula/gigantea</i>	<i>Caudammina ovula</i>	20	d	<i>Reussella szajnochae</i>
							c	<i>Rugoglobigerina</i> spp.
75	LATE	CAMPIANIAN	<i>Caudammina gigantea</i>	<i>Caudammina ovula/gigantea</i>	<i>Reussella szajnochae</i> 2	19	b	<i>A. intermedius</i>
							a	non-calcareous agglutinants
80	MIDDLE	EARLY	<i>Goesella rugosa</i>	<i>Goesella rugosa</i>	agglutinants dominant	18		unnamed (non-calcareous agglutinants)
85	EARLY	SANTONIAN	<i>Uvigerinammina jankoi</i>	<i>Uvigerinammina jankoi</i>	<i>Fenestrella</i> sp. 1	17		radiolaria

Fig. 5. A comparison between the assemblages from the Foula Sub-basin (well 205/10-2B), with the succession of Zones observed in the Western Tethys, Zumaya (Spain) and the northern North Sea (King, 1989; King *et al.*, 1989; Kuhnt *et al.*, 1992; Kuhnt & Kaminski, 1997).

Both species are known to range into the Upper Palaeocene in other areas (Kaminski *et al.*, 1988), so their LOs observed here are local events.

One striking feature of the correlation of the wells is the order of events of *C. ovula* and *R. szajnochae* 1 in well 206/5-1 with respect to the order described from wells 205/10-2B and 206/3-1 (Fig. 4). The true stratigraphic order of the LO events of *C. ovula* and *R. szajnochae* 1 remains an unsolved problem. Studies of more wells in the basin might give an indication of the stratigraphic utility of the LCO event of *C. ovula* and its position with respect to the LO of *R. szajnochae* 1.

Although the occurrence of planktonic and calcareous benthic foraminifera is affected by post-mortem preservation, there is a possibility that the three distinct Campanian and Maastrichtian calcareous foraminiferal influxes recognized in well 205/10-2B (Fig. 3) may serve as extra correlation markers. So far, these three events are only recognized in wells 205/10-2B and 206/5-1. A detailed study of assemblages in well 206/3-1 should reveal its correlative applicability for the Foula Sub-basin.

The stratigraphical succession of cosmopolitan species on the Northeast Atlantic margin displays many features in common between the studied sections, although there are notable local differences. In Fig. 5 the assemblages of four study areas are arranged from South to North for comparison. The study of the Foula Sub-basin provides an important link between the southern and northern regions of the North Atlantic. For the description of the assemblages in this study, and the zonation of King (1989) and King *et al.* (1989), only last occurrences of the index species are considered, whereas for the definition of zones in the Western Tethys, both last and first occurrences are used

(Kuhnt *et al.*, 1992; Kuhnt & Kaminski, 1997).

In the Western Tethys, the lower to middle Campanian is characterized by abundant *Goesella rugosa* (Hanzlíková, 1955). Only a few specimens of *G. rugosa* have been recovered from the Foula Sub-basin and the North Sea; therefore, other criteria are used for correlation in the northern Northeast Atlantic margins for this interval. In the Foula Sub-basin and northern North Sea *Caudammina gigantea* is very rare or absent, although *C. ovula*, the smaller, closely related form of *C. gigantea*, is commonly observed. The consistent occurrence of *Remesella varians* in all four studied areas makes it a reliable index species, although its occurrence might be limited in places by calcite dissolution (it is a calcite cemented agglutinated taxon). During the Palaeocene, *Spiroplectammina spectabilis* occurs throughout the whole Northeast Atlantic margin. However, during the late Palaeocene high abundances are only observed in the Foula Sub-basin and northern North Sea region. The additional observation of high abundances in the western Barents Sea implies that high abundances of this taxon may be confined to the late Palaeocene Boreal area (Nagy *et al.*, 1997).

The differences in abundances of certain index taxa suggest there are some noticeable palaeobiogeographical differences between Tethyan-related and more Boreal assemblages: *G. rugosa* and *C. gigantea* can be regarded as predominantly Tethyan species, whereas the high abundances of *S. spectabilis* during the late Palaeocene are typical of Boreal regions.

Basal Palaeocene unconformity

The lithostratigraphy and biostratigraphy provide constraints about the timing and extent of the early Palaeocene erosional

event in the Foula Sub-basin. The main cause for this event is the Icelandic mantle plume, which induced major thermal uplift in the Faeroe–Shetland Basin, causing regional extension. The extension was accompanied by uplift and erosion on the West Shetland margin with, simultaneously, deposition of the erosional products as submarine fans in the accelerated subsiding basin (Earle *et al.*, 1989). The uplift of the West Shetland Platform and Basin during the late early Palaeocene led to erosion in large areas of the Foula Sub-basin, resulting in the basal Palaeocene unconformity. Further to the NW, deep marine sedimentation still took place, which is deduced from seismic and well data in the Faeroe–Shetland Basin, indicating that the Palaeocene succession increases rapidly in thickness NW of the Flett Ridge (Mudge & Rashid, 1987). From early late Palaeocene times onward, marine sedimentation continued across almost the entire Faeroe–Shetland Basin. The Rona Ridge acted as the shelf edge from where submarine fans prograded into deeper parts of the basin (Knott *et al.*, 1993). Occasionally, erosional events took place on the Rona Ridge and in the West Shetland Basin. By the end of late Palaeocene times, marginal marine to shallow marine conditions prevailed into the early Eocene.

The lithostratigraphy and biostratigraphy of the three studied wells in the Foula Sub-basin fit adequately within this history of erosion and deposition. The area of the Flett Ridge (well 205/10-2B) is furthest away from the uplifted Shetland Platform and is only affected by the early Palaeocene erosional event. The hiatus encompasses Upper Maastrichtian to Lower Palaeocene sediments, as upper Lower Palaeocene sediments of the Sullom Formation rest unconformably on upper Maastrichtian sediments. Deposition of deep marine mudstones of the Upper Palaeocene Vaila and Lamba Formations continued after this event, while the central part of the Foula Sub-basin (well 206/3-1) and its SE margin (well 206/5-1) were subjected to continuing erosional events. During the late Palaeocene, deposition took place in a shallow marine environment with deposition of progradational and aggradational wedges of coastal plain facies of the Flett Formation into a relatively shallow sea (Knox *et al.*, 1997).

The lower limit of the Palaeocene erosional events is indicated by the index species observed in the Maastrichtian mudstones. In well 206/3-1 part of the latest Maastrichtian is still present, as is indicated by the abundance of *Pseudotextularia elegans* (nominant taxon of latest Maastrichtian Zone FCN21b of King *et al.*, 1989; Ritchie *et al.*, 1996). In the other two studied wells this species is absent in the highest Cretaceous samples analysed, indicating a late Maastrichtian age (Zone FCN21a of King *et al.*, 1989).

To conclude, a major erosional event in the Foula Sub-basin took place during the early Palaeocene. In well 205/10-2B the hiatus encompasses the late Maastrichtian to earliest Palaeocene; in well 206/3-1 uppermost Maastrichtian to lower upper Palaeocene sediments are eroded, and in well 206/5-1 upper Maastrichtian to Lower Palaeocene sediments are absent.

Palaeoenvironment

The microfaunal assemblages in the studied wells can be subdivided into calcareous and dominantly non-calcareous intervals. There are two scenarios which can explain this

observed pattern.

The first is that intervals with a diversified dominant agglutinated fauna could indicate phases of more restricted circulation in a deep water basin (Gradstein & Berggren, 1981). With restricted water circulation, the oxygen level at the sea floor drops and simultaneously the carbon dioxide level increases. This produces an acid reducing environment where calcium carbonate will easily dissolve; hence, calcareous benthic and planktonic foraminifera will be rare or absent in the sediment due to post-mortem dissolution. In contrast, intervals with abundant calcareous benthic and planktonic foraminifera are interpreted as reflecting periods with normal open marine circulation. Restricted water circulation can be induced in a semi-enclosed basin in relation to a low sea-level. The surface water circulation will be normal, while the deeper water column will be more stagnant. The influx of planktonic foraminifera will not be preserved in the sediment due to calcium carbonate dissolution. During periods of high sea level, deeper circulation of the basin is possible and the calcareous fauna will be preserved in the sediment.

As a second scenario, dysaerobic conditions at the seafloor can also be induced by high surface water productivity, most likely in relation to coastal upwelling. Decomposition of organic matter in the water column leads to oxygen deficiency and dissolution of calcium carbonate. In this case, intervals with a dominant agglutinated fauna would reflect periods of enhanced upwelling. However, the agglutinated foraminiferal fauna does not infer dysaerobic bottom water conditions during the non-calcareous intervals. Infaunal taxa are reported to be abundant in dysaerobic environments (Kaminski *et al.*, 1995), but in well 205/10-2B these taxa display low abundances throughout the studied section. Therefore, we can conclude that the bottom waters were well oxygenated or only slightly dysaerobic during the agglutinated foraminifera dominated intervals.

Whether the observations of planktonic foraminifera are related to post-mortem dissolution in a semi-enclosed basin or during periods of enhanced upwelling, they indicate influxes of North Atlantic surface water masses flowing northwards through the basin. Palaeogeographical patterns displayed by agglutinated foraminiferal fauna implies the same North Atlantic circulation: there is a close taxonomic affinity between the assemblages in the Foula Sub-basin and the assemblages from Trinidad (Kaminski *et al.*, 1988). For example, *Ammobaculites cf. jarvisi* (Cushman and Renz, 1946), *Goesella rugosa* and *Rzehakina epigona var. lata* (Cushman and Jarvis, 1928) are common in Trinidad and Venezuela, but very rare or unreported in the North Sea region.

In addition to foraminifera, diatom infillings and radiolarians are also present in the studied sections. They are especially abundant in the Lower Campanian. This biosiliceous event is known as the 'Lower to Middle Campanian Event' and is recognized worldwide (Moullade *et al.*, 1988; Thurow, 1988; Kuhnt *et al.*, 1989, 1992; Kuhnt, 1990). The enhanced biosiliceous surface water productivity reflects major oceanic events (upwelling, change in the Carbonate Compensation Depth, change in oceanic circulation or an increase in volcanic activity), which are mainly related to the formation of the Atlantic Basin, but not yet completely understood (Thurow, 1988).


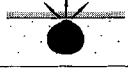


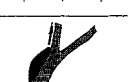


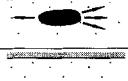

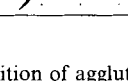
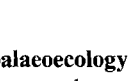
MORPHOTYPE	TEST SHAPE	MORPHO-GROUP	LIFE POSITION	FEEDING HABIT	ENVIRONMENT
	tubular	M 1	erect epifauna	suspension feeding	tranquil bathyal and abyssal with low organic matter flux
	globular	M 2 a	shallow infauna	suspension feeding - passive deposit feeding	bathyal and abyssal
	rounded trochospiral and streptospiral	M 2 b	surficial epifauna	active deposit feeding	shelf to marginal marine
	planoconvex trochospiral				
	elongate keeled	M 2 c	surficial epifauna	active deposit feeding	shelf to marginal marine
	flattened trochospiral	M 3 a	surficial epifauna	active and passive deposit feeding	high energy lagoon and estuary
	flattened planispiral and streptospiral				
	flattened irregular	M 3 b	surficial epifauna	passive deposit feeding	upper bathyal to abyssal
	rounded planispiral	M 4 a	surficial epifauna - shallow infauna	active deposit feeding	inner shelf to upper bathyal
	elongate subcylindrical	M 4 b	deep infauna	active deposit feeding	inner shelf to upper bathyal with increased organic matter flux
	elongate tapered				

Fig. 6. Morphogroup definition of agglutinated foraminifera (modified after Nagy *et al.*, 1995 and 1997).

Palaeobathymetry and palaeoecology

Using modern faunas as an analogue, relative proportions of the morphogroups, present in an assemblage, may be used to interpret changes in environmental parameters, such as water depth, current strength and organic flux to the sea floor. Morphogroups are defined on basis of the external morphology of the foraminiferal test. Agglutinated foraminiferal test shapes are thought to reflect differences in life position and feeding habit (Jones & Charnock, 1985; Nagy, 1992; Nagy *et al.*, 1995). The morphogroup classification of agglutinating foraminifera used here for the assemblages of well 205/10-2B, includes four main groups and eight morphotypes (based on work by Nagy *et al.*, 1995 and 1997), and is summarized in Fig. 6.

Morphogroup 1 comprises all epifaunal tubular taxa (belonging to the genera *Rhizammina*, *Rhabdammina*, and *Bathysiphon*) with a suspension feeding habit. Their erect life position is adapted to environments with a low organic flux to the seafloor. In modern settings, they are abundant in tranquil lower bathyal to abyssal environments (Schröder, 1986).

Three morphotypes are identified in morphogroup 2, involving a deposit feeding epifauna that often lives at or just below

the sediment surface, feeding on bacteria and detritus from the flocculent layer (Nagy, 1992). The first morphotype (2a) includes the unilocular globular taxa: *Saccamina* and *Psammosphaera*. The multilocular uniserial taxa, of which only single chambers are found in the samples, are included in this group (*Caudamina* and *Aschemocella*). Like the taxa of morphogroup 1, in modern oceans they are abundant at lower bathyal to abyssal water depths (Nagy *et al.*, 1995). In the second morphotype (2b), two different forms have been arranged. The first form comprises the more rounded trochospiral and streptospiral taxa (*Recurvoides* and *Thalmanammina*). The other form includes the planoconvex trochospiral forms with a rounded periphery (*Trochammina* and *Ammoanita*). In modern environments, morphotype 2b is most common in shelf and marginal marine waters (Nagy *et al.*, 1995). The elongate keeled forms of the third morphotype (2c) (*Spiroplectamina spectabilis* and *Spiroplectinella*) are interpreted as having also an epifaunal life habit.

The two morphotypes of morphogroup 3 contain the flattened taxa, of which the flat test is not caused by post-mortem compaction. The flattened trochospiral (*Lepidoparatrochammi-*

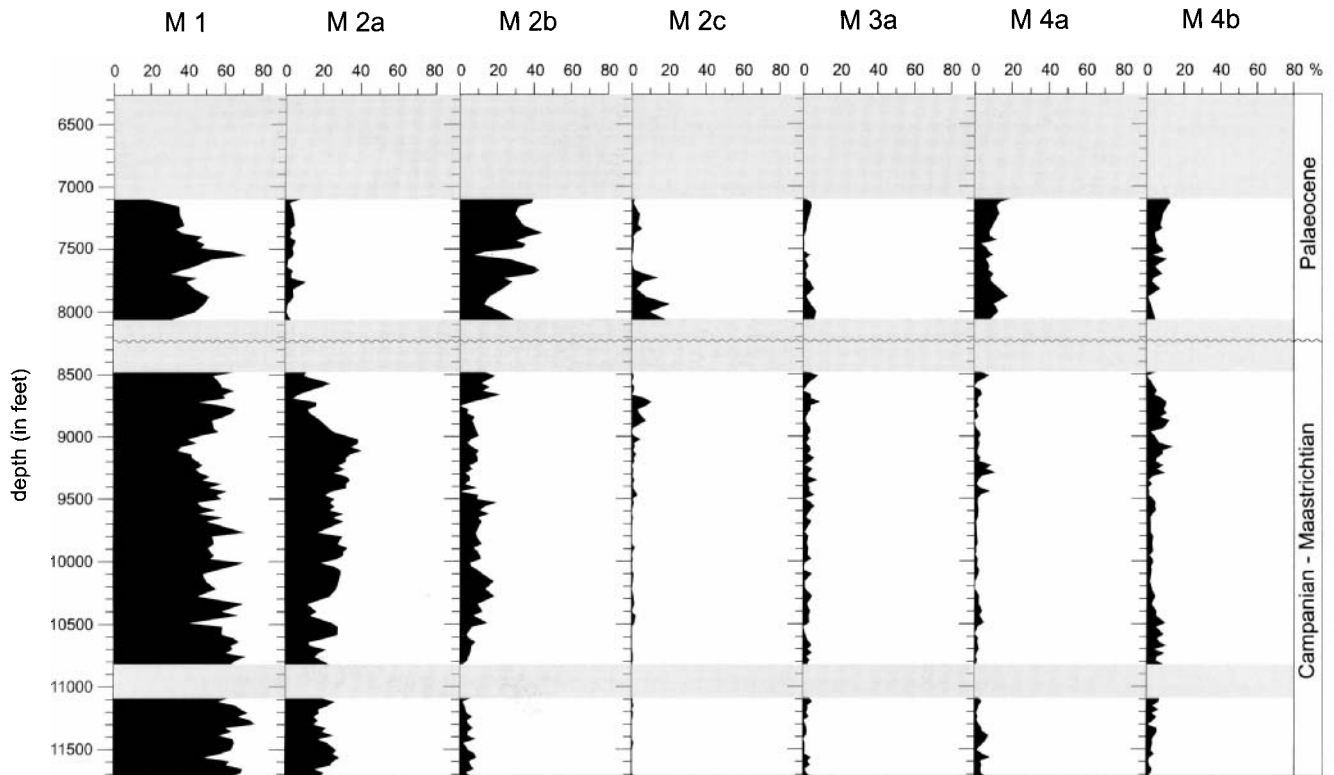


Fig. 7. Relative distribution (in percentage) of agglutinated foraminiferal morphogroups in well 205/10-2B. Grey shadings indicate almost barren intervals or interval where no samples were available (8060–8480 feet, 2457–2585 m).

na) and flattened planispiral and streptospiral forms (*Ammodiscus*, *Glomospira* and *Rzehakina*) are included in morphotype 3a. They live attached to elevated surfaces or seaweeds, or on the surface of the sediment (Nagy *et al.*, 1995). In modern faunas, they are most abundant in high energetic marginal marine environments (marshes and lagoons) (Nagy *et al.*, 1995). On the other hand, the single representative taxon of morphotype 3b in this study (*Ammolagena clavata*) is reported to be a significant contributor to the assemblage in upper bathyal and deeper environments (Schröder, 1986; Nagy *et al.*, 1995).

Morphogroup 4 comprises the infaunal forms and includes two different morphotypes. These forms are better adapted to life in areas of increased organic flux and higher nutrient supply (Nagy *et al.*, 1997). The planispiral forms with a rounded periphery belong to morphotype 4a (*Haplophragmoides*, *Reticulophragmium* and *Cribratomoides*). These forms live in the flocculent layer or in the sediment close to the sediment – water surface. However, these are minor contributors to the faunal assemblages from modern inner shelf to upper bathyal water depths (Nagy *et al.*, 1995). Both the multilocular, elongate subcylindrical (*Karrerulina*, *Remesella*, and *Gerochammina*) and elongate, tapered forms (*Reophax* and *Verneulinoides*) make up the contribution of morphotype 4b. Under normal conditions, these forms inhabit a deep infaunal habitat, where they scavenge the sediment for bacteria and detritus (Nagy, 1992; Nagy *et al.*, 1995). In addition, this group is reported to be abundant in areas where the surface layer of the sediment is affected by bottom currents or in dysaerobic environments (Kaminski, 1985;

Kaminski *et al.*, 1995). In general, they are most common in inner shelf to upper bathyal environments with moderate contributions to the faunal assemblages in lagoonal and marsh environments (Nagy *et al.*, 1995).

The results of the morphogroup analysis of the agglutinated foraminifera in well 205/10-2B are shown in Figure 7. The tubular taxa of morphogroup 1 are common throughout the studied section, with lower contributions in the Palaeocene interval. Frequency variations of this morphogroup are interpreted to reflect changes in the palaeobathymetric history of the studied site (Nagy *et al.*, 1997). In the Campanian–Maastrichtian part of the section this morphogroup is the main contributor to the assemblage. However, in the interval 9000–9300 feet (2743–2835 m) their relative proportion is somewhat lower, which suggests a shallowing of water depth in the area. On the other hand, the relative proportions of morphotype 2a are increased in the same interval. Together with the taxa of morphogroup 1, the taxa of morphotype 2a are most abundant in lower bathyal and abyssal environments in modern oceans (Nagy *et al.*, 1995). Based on the relative proportions of these two morphotypes, they indicate contradictory bathymetric trends. There is no other evidence which suggests a shallower water depth during this interval. Calculation of the total number of specimens of taxa representing a morphogroup per studied gram of a sample reveals that there is a small increase in the number of morphotype 2a per gram in the interval 8900–9300 feet (2713–2835 m), while the numbers of morphogroup 1 per gram stay constant in the same interval. So the trend observed in

the relative proportions of morphogroup 1 is related to the closed sum effect due to a small increase in the absolute abundance of morphotype 2a. In conclusion, a lower bathyal depositional environment is inferred for the whole Campanian and Maastrichtian interval.

The difference in the relative proportion of the morphogroups between the intervals above and below the unconformity is most obvious from morphotype 2a: in the Palaeocene part (7100–8060 feet, 2164–2457 m) this group is almost absent (Fig. 7). In the same interval of the studied section morphogroup 1 is still common, but is present in lower proportion as in the Cretaceous interval. Higher abundances in the Palaeocene interval of the epifauna and shallow infauna (morphotypes 2b and 4a respectively) indicate a shallower depositional environment in a middle to upper bathyal water depth (Nagy *et al.*, 1995).

SUMMARY

Among the three studied wells located in the Foula Sub-basin on the western margin of the Shetland Islands, well 205/10-2B is chosen as a stratigraphic reference section for the Campanian–Palaeocene interval. A total of 153 agglutinating species and taxa in open nomenclature taxa are recognized. Based on the succession of shelly microfossils (benthic and planktonic foraminifera, diatoms and radiolarians) the section can be subdivided into ten stratigraphically distinct assemblages. For correlation and palaeoceanographic purposes, this study area provides an important link between the northern and southern areas of the northeast Atlantic margin.

The composition of the foraminiferal assemblages indicates that deposition took place in a well oxygenated, deep marine environment with influxes of North Atlantic surface water masses. Analysis of agglutinated benthic foraminiferal morphogroups in the reference section indicates a shallowing of the basin over the widespread lower Palaeocene unconformity.

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