

Campanian and Maastrichtian biostratigraphy in the Foula Sub-Basin, west of the Shetland Islands (UK)

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Abstract: A detailed biostratigraphic zonation scheme is proposed for the Foula Sub-basin, located west of the Shetland Islands (U.K. continental shelf). Six stratigraphically distinct Campanian and Maastrichtian zones are described based on the succession of last occurrence events of benthic and planktonic foraminifera and siliceous microfossils in three studied wells (i.e. well 205/10-2B, 206/3-1 and 206/5-1). The distribution of the zones in the Foula Sub-basin is indicated by correlation between the three wells. Despite some local differences, the biostratigraphy of the Foula Sub-basin displays many features in common with the biostratigraphy of studied sections in the Western Tethys, the northern North Sea Basin and on the Norwegian margin, and the basin is therefore an important link between the southern and northern areas of the Northeast Atlantic margin. The biostratigraphy also provides constraints about the timing and extent of the unconformities in the Foula Sub-basin.

Keywords: Foula Sub-Basin, Campanian, Maastrichtian, Microfossils, Biostratigraphy, Biozonation

1. INTRODUCTION

The Foula Sub-basin is part of the Faeroe-Shetland Basin, which is situated on the Northwest European Atlantic margin, west of the Shetland Islands (U.K. continental shelf; Fig. 1). The basin was a major Cretaceous depocentre where thick successions of turbidite derived mudstones from the Upper Cretaceous Shetland Group accumulated. This area is of great interest due to several hydrocarbon findings. However, despite the need for a good biostratigraphic framework to date the monotonous successions of mudstones of the Upper Cretaceous Shetland Group, only faunal events from the area west of the Shetland Islands have been described (RIDING, 1996). Therefore, the objective of this study is to propose a Campanian to Maastrichtian biostratigraphic zonation scheme for a sub-basin of the Faeroe-Shetland Basin, the Foula Sub-basin. Ditch cuttings from three wells have been studied quantitatively, of which well 205/10-2B is taken as a reference section because of the thick succession of Campanian-Maastrichtian sediments present.

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2. STUDY AREA

2.1. Geological setting

The Foula Sub-basin is part of the Faeroe-Shetland Basin, which is situated on the Northwest European Atlantic margin, west of the Shetland Islands (U.K. continental shelf). Fig. 1 shows the location and geological structure of the study area. The Faeroe-Shetland Basin, which is a deep, asymmetric half-graben between the Rona Ridge and Mid Faeroe Ridge, was the location of a major Cretaceous depocentre. The half-graben confined between the Flett Ridge and Rona Ridge is referred to as the Foula Sub-basin (GRANT et al., 1999). The ridges in the Faeroe-Shetland Basin are structural features in the Precambrian crystalline basement, blanketed by thick sequences of Lower Cretaceous to Recent sediments. The ridges are bounded by extensional normal faults (Flett Fault and Rona Fault) which were active mainly during Early Cretaceous times, although fault activity along the Rona Ridge continued into Campanian times (DEAN et al., 1999).

2.2. Geological history

The development of the Faeroe-Shetland Basin is strongly related to the opening history of the North Atlantic Basin. Extensive reviews of the structural and stratigraphic devel-

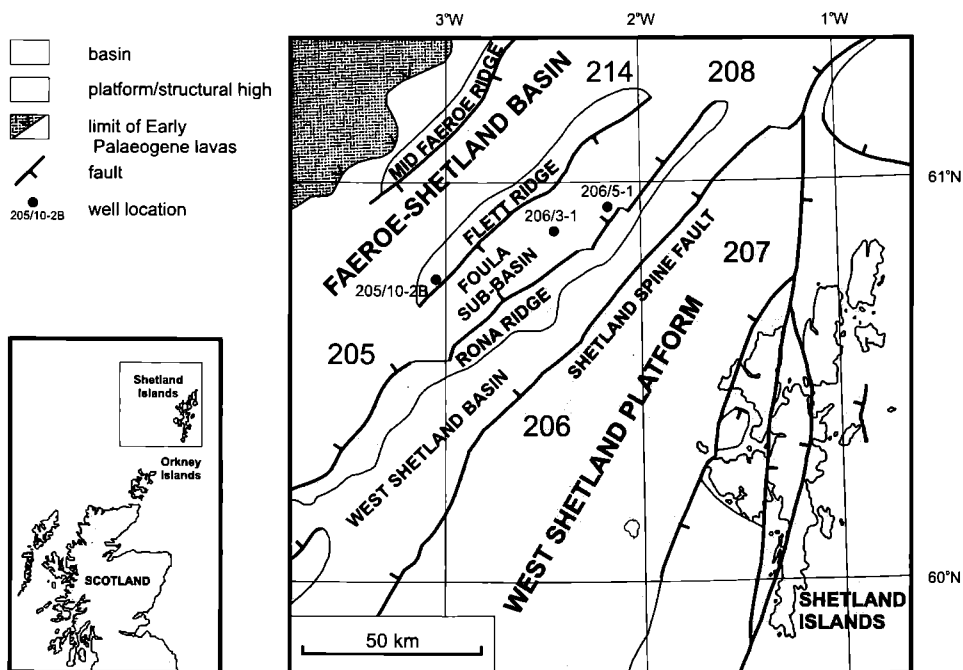


Fig. 1: Location map and detail of pre-Paleogene structure of the area west of the Shetland Islands (after RITCHIE et al., 1996 and GRANT et al., 1999).

opment of the Faeroe-Shetland Basin have been given by DUINDAM & VAN HOORN (1987), HITCHEN & RITCHIE (1987), MUDGE & RASHID (1987), EARLE et al. (1989), TURNER & SCRUTTON (1993), DEAN et al. (1999) and GRANT et al. (1999); therefore, only a short summary is given here.

The Faeroe-Shetland Basin was part of the northern proto-North Atlantic (Greenland – Norwegian rift, including the Rockall Trough, Faeroe-Shetland, Møre, Vøring, Løfoten, East Greenland and West Barents Sea Basins) and it has experienced a complex geological history with several rifting events occurring during the Mesozoic, all of which were related to the opening of the North Atlantic. The Faeroe-Shetland Basin has been affected by at least six rifting events in Permo-Triassic to Paleocene times, with the major rifting events commencing during the Early Cretaceous.

Basin development in the area west of the Shetland Islands commenced in Devonian times, with minor extension and deposition in continental settings. In the West Shetland Basin (see Fig. 1 for location), sequences of Devonian to Early Carboniferous aeolian and fluvial beds overlie the Precambrian basement, hosting the Clair oil field on the Rona Ridge. It is not known if there was already extension in the main Faeroe-Shetland Basin at that time, because the configuration of the early development of the Foula Sub-basin is unknown due to poor seismic imaging at deeper levels. Uplift and erosion during the Late Carboniferous resulted in widespread erosion. Renewed rifting and subsidence occurred during Permian to Early Triassic times, with deposition taking place primarily in continental settings (evaporitic and clastic red bed sequences). This Triassic rifting event was succeeded by post-rift Lower-Mid Jurassic fluvio-deltaic to shallow marine fan deposition, reflecting the first marine incursion into the area west of the Shetland Islands. The penetration in well 206/5-1 (see Fig. 1 for location) of a sequence of slumped Upper Jurassic submarine fan deposits resting disconformably on a thick Middle Jurassic sequence, suggests a minor Mid Jurassic rifting event and a significant Late Jurassic rifting event. However, neither seismic evidence nor extensive well control is available to actually demonstrate any Jurassic rifting event, although the present data indicate there was some fault activity on the Flett and Rona Faults. The supposed rifting event, which commenced in the early part of the Late Jurassic, is succeeded by the development of a post-rift deposition of deep marine anoxic shales (Kimmeridge Clay), indicating rising relative sea levels. The occurrence of a widespread unconformity at the base of the Cretaceous indicates that basement highs (e.g. the Rona Ridge) were subjected to local uplift and erosion.

Rifting intensified in the Faeroe-Shetland Basin in the Early Cretaceous, with the main active period occurring during Valanginian-Albian. This episode of rifting is strongly related to the intensive extension in the Rockall Trough, where rifting continued into the Late Cretaceous (Santonian/Campanian). In the Faeroe-Shetland Basin, the complete Cretaceous depositional sequence is fault-controlled, with activity concentrated along the Flett and Rona Faults. Early Cretaceous sedimentation took place in a deep marine environment, with deposition of submarine fan derived slump deposits close to the active faults, intercalated with hemipelagic muds. A renewed fault-controlled extensional event occurred on the Rona Fault during Cenomanian and Turonian times, characterised by a renewed influx of turbiditic derived sandstones into the Foula Sub-basin. Since then, the Faeroe-Shetland Basin has been characterised by thermal subsidence with the deposition of a thick sequence of homogenous mudstones. This was only interrupted by a distinct

pulse of renewed faulting and associated uplift along the Rona Fault during the Campanian, resulting in a hiatus over the structurally highest parts of the Rona Ridge.

The last rifting event in the Faeroe-Shetland Basin coincided with the development of the Icelandic mantle plume during the Paleocene and early Eocene, which was situated under East Greenland at that time (EBDON et al., 1995; NADIN et al., 1997). This rifting event is characterised by thermal doming, resulting in significant extension, as well as regional uplift. This caused widespread erosion on the uplifted West Shetland margin and deposition of submarine fans in the more rapidly subsiding Faeroe-Shetland Basin. The development of the Icelandic mantle plume was accompanied by voluminous sub-aerial volcanism (Thulean phase) north of the Faeroe Islands (CHALMERS et al., 1995) with effusive volcanism succeeded by a final phase of explosive volcanism (ROBERTS et al., 1984). The thermal dome collapsed in the early Eocene with the onset of sea-floor spreading between Greenland and Northwest Europe. Since this event, renewed thermal subsidence led to deep-water conditions. The thermal subsidence was only perturbed by a minor late Eocene to early Oligocene inversion event along some growth faults associated with the Flett and Rona Ridges.

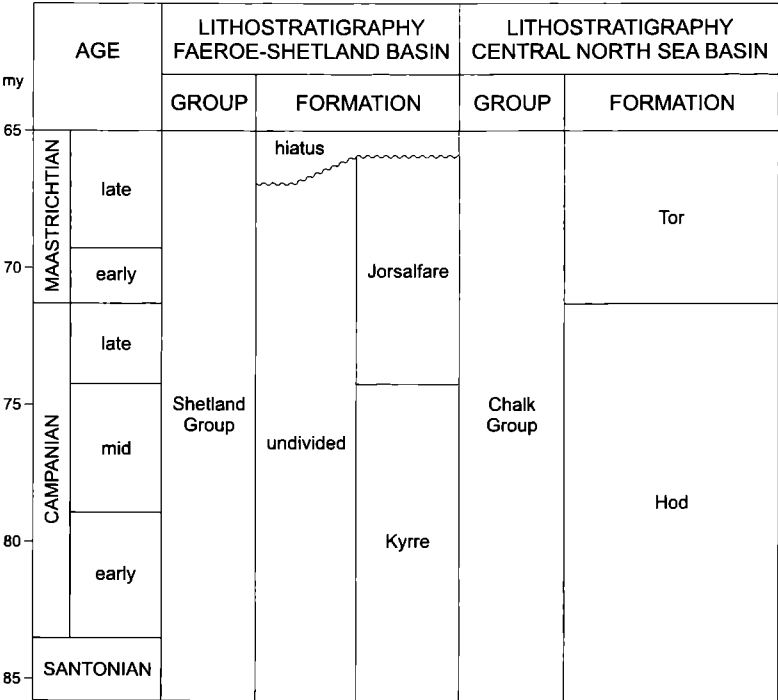


Fig. 2: Comparison between lithostratigraphy of the Faeroe-Shetland Basin (after RITCHIE et al., 1996) and the Central North Sea Basin (after DEEGAN & SKULL, 1977). Timescale is after GRADSTEIN & OGG (1996).

2.3. Lithostratigraphy

The Mesozoic lithostratigraphy of the area west of the Shetland Islands was revised recently by RITCHIE *et al.* (1996). In the Faeroe-Shetland Basin, the Upper Cretaceous Shetland Group consists of a monotonous succession of light to dark grey deep marine calcareous and non-calcareous mudstones with thin bands of argillaceous limestone and dolomite. The Shetland Group is laterally equivalent to the Chalk Group in the Central North Sea Basin (see Fig. 2). Based on well log transitions, the Shetland Group is divided into the Kyrre and Jorsalfare Formations in parts of the Faeroe-Shetland Basin. However, in the Foula Sub-basin it is difficult to define the formation boundaries in the Campanian and Maastrichtian succession of mudstones, and therefore the Shetland Group is undivided. The upper boundary of the Maastrichtian calcareous mudstones is characterised by a very distinct well log transition, reflecting an unconformity. Due to thermally induced uplift in the early Paleocene to early Eocene (EBDON *et al.*, 1995; NADIN *et al.*, 1997), the area west of the Shetland Islands was subjected to erosion which resulted in a stratigraphic gap encompassing upper Maastrichtian and lower to upper Paleocene sediments in most parts of the Foula Sub-basin.

3. MATERIAL AND METHODS

The biostratigraphy is based on ditch cutting samples from three wells from the Foula Sub-basin: wells 205/10-2B, 206/3-1 and 206/5-1 (see Fig. 1 for location). The 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°45'43.235"N and 03°03'21.812"W with Britoil plc as the operator. Well 206/3-1 (Amoco, U.K.) was also drilled during 1984 at 60°52'42.092"N and 02°26'23.734"W, while well 206/5-1 (Shell, U.K.) was drilled during 1976 at 60°50'25.98"N and 02°10'14.26"W. All depths of the samples are reported in feet below rotary kelly bushing. Most of the samples are spaced at a 30 ft. (9.1 m) interval. The samples, ranging in dry weight from 33 to 77 grams, 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. Because an 18 ³/₈ inches casing is placed at a depth of 8349 ft. in well 205/10-2B, no samples were available for the interval near the casing (8060–8420 ft.). In the lower part of the studied section of well 205/10-2B, samples are excluded from the analysis (10820–11090 ft.) due to the occurrence of dolerite dykes. In total, 192 samples have been examined and altogether 142 agglutinating species, 148 calcareous benthic foraminiferal species and 21 planktonic foraminiferal species (including taxa in open nomenclature) were recognised. For the biostratigraphy, only last occurrence events (LO) and last common occurrence events (LCO) of taxa are reliable, due to the possibility of downhole caving. The depths of the unconformities are taken from studied well log data and seismic interpretation. Although the depth labels of ditch cutting samples do not directly correlate to the well log depth, these are accurate within a 30 ft. interval.

4. RESULTS

In this study, the samples in the three wells are dominated by agglutinated foraminifera, most of which are long-ranging, cosmopolitan species. The tubular taxa (*Bathysiphon* spp., *Rhabdammina* spp. and *Rhizammina* spp.) are dominant throughout the studied sections, with common occurrences of globular taxa (*Psammospaera* spp., *Saccammina* spp. and *Caudammina* spp.). There are three distinct intervals with common to abundant calcareous benthic and planktonic foraminifera. Besides foraminifera, siliceous microfossils occur throughout the studied interval, with characteristic high abundances of them in the lower part of the sections.

4.1. Biozonation scheme

Well 205/10-2B is taken as a reference section for the biostratigraphy, because of the thick succession of Campanian to Maastrichtian sediments present. A composite section, which maximises the stratigraphic resolution, has been created by adding biostratigraphic information from the other two studied wells. The resulting Campanian to Maastrichtian succession of benthic and planktonic foraminifera, diatoms and radiolarians has been subdivided into six stratigraphically distinct assemblages, based on abundances of dominant taxa and the last occurrence events of characteristic foraminiferal and biosiliceous dominant taxa (see Fig. 3). Chronostratigraphic assignment of the bio-events is based on reports from the northern North Sea Basin (KING et al., 1989; WILKINSON et al., 1993), the area west of the Shetland Islands (RIDING, 1996), and from the Norwegian margin (GRADSTEIN et al., 1999). Below, a discussion of the six successive Campanian to Maastrichtian zones is given. The chronostratigraphy and distribution of index taxa is shown in Fig. 3.

4.1.1. *Fenestrella bellii* Range Zone

Age: early Campanian.

Lower boundary: the LCO of shell debris (calcite prisms) of *Inoceramus* spp.

Upper boundary: the LO of the characteristic pyritised mould of the diatom *Fenestrella bellii*.

This zone is characterised by very abundant occurrences of pyritised infillings of radiolarians and diatom species, amongst which is the characteristic conical shaped mould of *Fenestrella bellii* (see Plate 1/8). An alternative marker for the LCO of shell debris of *Inoceramus* spp. is the LO of large spherical siliceous radiolarians near the base of this zone (see Fig. 3). The occurrence of *F. bellii* is also recognised in the lower Campanian sediments of the Haltenbanken area on the Norwegian margin (see Fig. 5; GRADSTEIN et al., 1999). KING et al. (1989) did not separate this biosiliceous assemblage from the unnamed agglutinated foraminiferal dominated interval (Zone FCN18), although this zone might also correlate with part of the 'radiolaria' Zone FCN17 (see Fig. 5). The early Campanian age corresponds to a widespread biosiliceous event recognised in the North Atlantic and western Tethys, which is referred to as the 'Lower to Middle Campanian Event' (MOULLADE et al., 1988; THUROW, 1988; KUHN et al., 1989 and 1992; KUHN, 1990).

On the Norwegian margin, the LCO of *Inoceramus* spp. shell debris marks the Santonian/Campanian boundary (GRADSTEIN et al., 1999). For this study in the Foula Sub-basin, little information is available about the Santonian assemblages, as only the lowermost studied samples contain common shell fragments of *Inoceramus* spp. A similar assemblage has also been recognised on the Norwegian margin, where it would correlate with the *Inoceramus* LCO Zone of GRADSTEIN et al. (1999).

The zone is dominated by agglutinated foraminifera, with abundant *Rhizammina* spp. and *Psammosphaera* spp. Other species which are common in the samples include *Bathysiphon discreta*, *Saccamina* spp., *Ammodiscus* spp., *Glomospira* spp., *Caudamina ovula*, *C. ovuloides*, *Haplophragmoides* spp., *Recurvoides* spp., *Trochammina* spp., *Karrerulina/Gerochammina* spp. group and *Verneuilinoides* spp. The abundant biosiliceous contribution to the assemblage includes pyritised moulds of spherical radiolarians, *Stellarima microtrias*, *Fenestrella bellii*, diatom sp. 1 and other pyritised diatoms, as well as small and big spherical siliceous radiolarians.

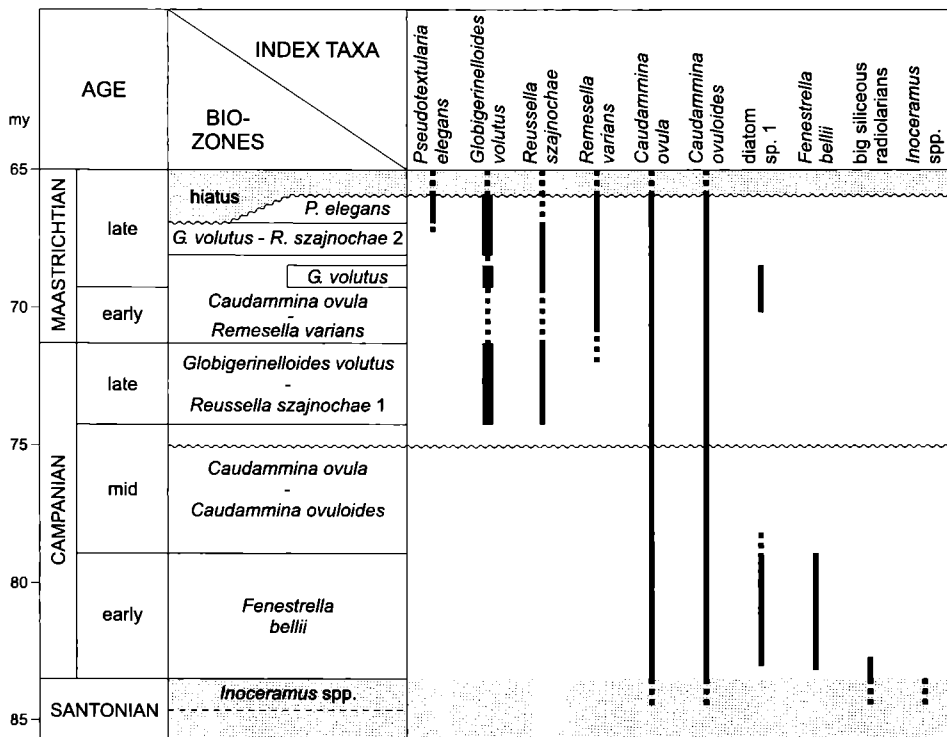


Fig. 3: Zonation scheme for the Foula Sub-basin with distribution of index taxa. Grey shading indicates intervals which are not studied. The mid-Campanian unconformity is taken from studied seismic sections. Timescale is after GRADSTEIN & OGG (1996).

4.1.2. *Caudammina ovula* – *Caudammina ovuloides* Partial-range Zone

Age: mid Campanian.

Lower boundary: the LO of the characteristic pyritised mould of the diatom *Fenestrella bellii*.

Upper boundary: the change from a non-calcareous agglutinated foraminifera dominated fauna with *Caudammina ovula* and *Caudammina ovuloides* to a calcareous foraminiferal rich assemblage above.

This zone is characterised by long-ranging non-calcareous agglutinated taxa, including *Caudammina ovula* and *Caudammina ovuloides*. Both species have been reported to occur already during Cenomanian and Turonian times respectively (KUHNT et al., 1992; GRADSTEIN et al., 1999), with *C. ovuloides* ranging into the upper Paleocene and *C. ovula* into the lower Eocene (KAMINSKI et al. 1988; CHARNOCK & JONES, 1990). In the lower part of the zone, pyritised moulds of diatoms and spherical radiolarians are still abundant. The top of this interval is characterised by a change to a calcareous foraminiferal rich fauna. The faunal turnover is a distinct event which has been recognised over a large area. The zone correlates to the unnamed agglutinated foraminifera dominated zones in the northern North Sea Basin (upper part of Zone FCN18: KING et al., 1989) and on the Norwegian margin (GRADSTEIN et al., 1999) (see Fig. 5).

The foraminiferal fauna is dominated by *Rhizammina* spp. and *Psammosphaera* spp., with additional common occurrences of *Bathysiphon discreta*, *Rhaddammina* spp., *Saccammina* spp., *Ammodiscus* spp., *Glomospira* spp., *Caudammina ovula*, *C. ovuloides*, *Haplophragmoides* spp., *Paratrochamminoides* spp., *Recurvoides* spp., *Trochammina* spp., *Karrerulina/Gerochammina* spp. group and *Verneuilinoides* spp. In the lowest part of the zone pyritised moulds of radiolarians and diatoms are still abundant.

4.1.3. *Globigerinelloides volutus* – *Reussella szajnochae* 1 Acme Zone

Age: late Campanian.

Lower boundary: the change from an agglutinated foraminifera dominated fauna to a calcareous foraminiferal rich assemblage above.

Upper boundary: the change from a dominantly calcareous foraminiferal fauna to a dominantly agglutinated foraminiferal assemblage above, associated with the LO of *Reussella szajnochae*.

This zone is characterised by abundant occurrences of *Globigerinelloides volutus* and other planktonic and calcareous benthic foraminifera, including *Reussella szajnochae* (Fig. 3). Throughout most of the North Sea Basin and west of the Shetland Islands, the occurrence of *R. szajnochae* in the top of the Campanian is a widespread and easily recognised biomarker event, with its LO used locally to identify the Campanian/Maastrichtian boundary (see Fig. 5: top of Zone FCN19 of KING et al., 1989; WILKINSON et al., 1993; RIDING, 1996). However, this biomarker event is not the true LO event of *R. szajnochae*, as this species reappears again in younger strata. In the North Sea Basin this species is reported to range from late Campanian into mid Maastrichtian times, although it is absent during the early Maastrichtian (KING et al., 1989; WILKINSON et al., 1993). In this study, this pattern has only been clearly observed in the reference well 205/10-2B

and well 206/5-1: in well 206/3-1, this species is also present in lower Maastrichtian sediments. More wells from the Foula Sub-basin need to be studied to determine the stratigraphic significance of this LO event of *R. szajnochae*.

The foraminiferal fauna in this assemblage is dominated by calcareous foraminifera. The abundant planktonic foraminifera in this assemblage are *Globigerinelloides volutus* and *Archaeoglobigerina blowi*, with smaller numbers of *Heterohelix globulosa*, *Hedbergella holmdelensis*, *Globotruncana arca* and *Archaeoglobigerina cretacea*. From the numerous calcareous benthic foraminiferal taxa, the most common species include *Dentalinoides* spp., *Lagena globosa*, *Bolivinooides* spp., *Praebulimina reussi*, *Pyramidina* spp., *Reussella szajnochae*, *Gavelinopsis bembix*, *Nuttallides* spp., *Pullenia* spp., *Osangularia* sp. cf. *O. alata*, *O. glabrata*, *O. texana*, *Gyroidinoides* spp., *Gavelinella sandidgei* and *Gyroidina* spp. The agglutinated foraminiferal fauna increases in diversity, although it is still dominated by long-ranging taxa: *Rhizammina* spp. and *Psammosphaera* spp., with additional common occurrences of *Bathysiphon discreta*, *Nothia* spp., *Rhabdammina robusta*, *Rhabdammina* spp., *Saccammina grybowskii*, *Saccammina* sp. cf. *S. placenta*, *Glomospira* sp. cf. *G. irregularis*, *Glomospira* spp., *Subreophax* spp., *Caudammina ovula*, *C. ovuloides*, *Paratrochamminoides* spp., *Recurvooides* spp., *Trochammina* spp. and the *Karrerulina/Gerochammina* spp. group. Furthermore, pyritised moulds of diatoms, *Stellarima microtrias* and spherical radiolarians are common.

4.1.4. *Caudammina ovula* – *Remesella varians* Partial-range Zone

- Age:** early Maastrichtian and early part of late Maastrichtian.
- Lower boundary:** the change from a dominantly calcareous foraminiferal fauna to a predominantly agglutinated foraminiferal fauna above (more than 90% of the total foraminiferal assemblage).
- Upper boundary:** the increase in abundance of calcareous foraminifera, characterised by the reappearance of common occurrences of *Reussella szajnochae*.

This zone is characterised by the occurrence of *Caudammina ovula* and *Remesella varians*. Both taxa are long-ranging, although the presence of *R. varians* is limited in relation to the availability of calcium carbonate, because it is a calcareous cemented taxon. In the Northeast Atlantic, the occurrence of *R. varians* is a useful indicator for the late Maastrichtian (KAMINSKI et al., 1988; KUHNT et al., 1989 and 1992; KUHNT & KAMINSKI, 1997), although it is reported to range into the lower Paleocene in many study areas (KING, 1989; CHARNOCK & JONES, 1990; KUHNT, 1990; KUHNT & KAMINSKI, 1997; OLSZEWSKA, 1997).

In this zone, a three-fold subdivision can be made based on the abundance of calcareous benthic and planktonic foraminifera (Fig. 3). The lower part of this zone is dominated by agglutinated foraminifera. This part of the *C. ovula* – *R. varians* assemblage is equivalent to Zone FCN20a of KING et al. (1989) (Fig. 5). Subsequently, there is a change in assemblage composition to dominantly calcareous foraminifera again. In the northern North Sea Basin and west of the Shetland Islands, this change from non-

calcareous forms to calcareous species is correlated with the lower/upper Maastrichtian boundary (see Fig. 5: upper boundary of Zone FCN20a of KING et al., 1989; RIDING, 1996). This calcareous foraminiferal rich interval, dominated by *G. volutus* and other planktonic foraminifera, correlates with zones FCN20b and FCN20c of KING et al. (1989) (see Fig. 5). In the upper part of the zone the fauna is dominated by agglutinated foraminifera again. This part of the *C. ovula* – *R. varians* Partial-range Zone correlates with the lower part of Zone FCN20d of KING et al. (1989).

The composition of the assemblage is quite similar to the previous described assemblage, apart from a few differences. The planktonic foraminiferal taxa in the calcareous foraminiferal rich interval of this assemblage are dominated by *Heterohelix globulosa*, *H. planata*, *Globigerinelloides volutus*, *Archaeoglobigerina blowi* and *A. cretacea*, with in addition common occurrences of *Laeviheterohelix dentata*, *L. glabrans*, *Hedbergella holmdelensis*, *Globotruncana arca* and *Globotruncanella petaloidea*. From the numerous calcareous benthic foraminiferal taxa, the most common species include *Dentalinoides* spp., *Lagena globosa*, *Praeulimina reussi*, *Pyramidina* spp., *Gavelinopsis bembix*, *Nuttallides* spp., *Pullenia* spp., *Allomorphina* spp., *Quadriformina* spp., *Valvulabamina* spp., *Osangularia* sp. cf. *O. alata*, *O. glabrata*, *O. texana*, *Gyroidinoides* spp. and *Gavelinella sandidgei*. The agglutinated foraminiferal fauna is dominated by *Rhabdammina* spp., *Rhizammina* spp., *Psammosphaera* spp., *Recurvoides* spp., with additional common occurrences of *Bathysiphon discreta*, *Nothia* spp., *Rhabdammina robusta*, *Saccamina grzybowskii*, *S. placenta*, *Saccamina* sp. cf. *S. placenta*, *Ammodiscus* spp., *Glomospira* sp. cf. *G. irregularis*, *Glomospira* spp., *Subreophax* spp., *Caudammina ovula*, *C. ovuloides*, *Paratrochamminoides* spp., *Eratidus* sp., *Trochammina* spp., the *Karrerulina/Gerochammina* spp. group, *Verneuilinoides* spp. and *Remesella varians*. Furthermore, pyritised moulds of spherical radiolarians, *Stellarima microtrias* and diatom sp. 1 are common.

4.1.5. *Globigerinelloides volutus* – *Reussella szajnochae* 2 Acme Zone

Age: early part of late Maastrichtian.

Lower boundary: the increase in proportions of calcareous foraminifera.

Upper boundary: the first common occurrence of *Pseudotextularia elegans*, associated with the LO of the reappearance of common occurrences of *Reussella szajnochae*.

This zone contains high abundances of many calcareous benthic and planktonic foraminiferal taxa with higher relative proportions of planktonic foraminifera as in the previous calcareous foraminiferal rich intervals (more than 40%). The few agglutinated foraminiferal taxa are not so abundant.

The reappearance of *R. szajnochae* has been reported from the early part of the late Maastrichtian in the northern North Sea Basin (see Fig. 5: Zone FCN20d of KING et al., 1989; WILKINSON et al., 1993) and Faeroe – Shetland Basin (RIDING, 1996). However, due to its rarity in places and the lack of independent biostratigraphic controls, the precise stratigraphical position of the LO of this biomarker within the Maastrichtian is not clear, although it is assumed to mark the boundary between the early and late part of the late Maastrichtian (WILKINSON et al., 1993; RIDING, 1996). From the Norwegian margin, this

taxon is reported from the early Maastrichtian, ranging into late Maastrichtian in the southern part where few specimens occur in the late Maastrichtian *Pseudotextularia elegans* Range Zone (GRADSTEIN et al., 1999). It is therefore suggested that this biomarker ranges into younger strata in regions south of the Norwegian margin study area (GRADSTEIN et al., 1999). This zone correlates best with Zone FCN20d of the North Sea Basin (KING et al., 1989) and the *Globigerinelloides volutus* Zone of mid-Norway (GRADSTEIN et al., 1999) (see Fig. 5).

This zone is distinguished from the late Campanian *G. volutus* – *R. szajnochae* 1 Acme Zone assemblages by the presence of *Remesella varians*, and it differs from the latest Maastrichtian calcareous foraminiferal rich faunas by the absence of common occurrences of *Pseudotextularia elegans*. In cases where the sediments of the overlying *P. elegans* Range Zone are eroded during the basal Paleogene erosional event, the upper boundary of this zone is characterised by a very distinct change in faunal composition. Paleocene assemblages are characterised by abundant occurrences of *Cribrostomoides* spp., *Haplophragmoides* spp., *Recurvoides* spp., *Trochammina* spp. and *Karrerulina* spp. Reworked Late Cretaceous planktonic foraminifera might occur; however, the Paleocene age is confirmed by the presence of *Subbotina* spp.

The planktonic foraminiferal fauna in this zone is dominated by *Heterohelix globulosa*, *Globigerinelloides volutus*, *Hedbergella holmdelensis*, *Archaeoglobigerina blowi* and *A. cretacea*. Species which are common in the interval include *Heterohelix planata*, *Laeviheterohelix dentata*, *L. glabrans*, *Hedbergella monmouthensis* and *Globotruncanella petaloidea*, with only few representative specimens of *Rugoglobigerina rugosa*. From the numerous calcareous benthic foraminiferal taxa, the most common species include *Dentalinoides* spp., *Lagena globosa*, *Lagena* spp., *Bolivinooides* spp., *Praebulimina arkadelphia*, *P. reussi*, *Pyramidina* spp., *Reussella szajnochae*, *Gavelinopsis bembix*, *Pullenia jarvisi*, *Allomorphina* spp., *Quadriformina* spp., *Valvalabamina* spp., *Osangularia* sp. cf. *O. alata*, *O. glabrata*, *O. texana*, *Gyroidinoides* spp., *Gavelinella sandidgei* and *Gyroidina* spp. The assemblage also contains common *Bathysiphon discreta*, *Rhabdammina* spp., *Rhizammina* spp., *Psammosphaera* spp., *Saccammina grzybowskii*, *Saccammina* sp. cf. *S. placenta*, *Ammodiscus* spp., *Glomospira* spp., *Caudammina ovula*, *C. ovuloides*, *Bolivinopsis* sp., *Spiroplectammina spectabilis*, *Trochammina* spp., *Verneuilinoides* spp. and *Remesella varians*. Furthermore, pyritised moulds of spherical radiolarians and *Stellarima microtrias* are common.

4.1.6. *Pseudotextularia elegans* Range Zone

Age: latest part of late Maastrichtian.

Lower boundary: the lowest common occurrence of *Pseudotextularia elegans*.

Upper boundary: the LO of in-situ Late Cretaceous planktonic foraminifera.

Only in well 206/3-1 sediments of this zone are present. This zone is characterised by abundant occurrences of planktonic foraminifera, amongst which is *Pseudotextularia elegans* (Fig. 3). This taxon is reported to be restricted to the uppermost Maastrichtian (KING et al., 1989; RIDING, 1996). The stratigraphic range of this taxon could be artificially extended downhole due to the possibility of caving in the borehole. Therefore, the lower

boundary of this zone is taken at the lowest common occurrence of *P. elegans*. This zone correlates to Zone FCN21b in the North Sea Basin (KING et al., 1989) and the zone of the same name on the mid-Norwegian margin (GRADSTEIN et al., 1999) (see Fig. 5). In well 206/3-1, the upper boundary of this zone is an erosional contact with upper Paleocene sediments, characterised by sediments which are almost barren of any microfossils. Throughout the Foula Sub-basin, the faunal change across the basal Paleogene uncon-

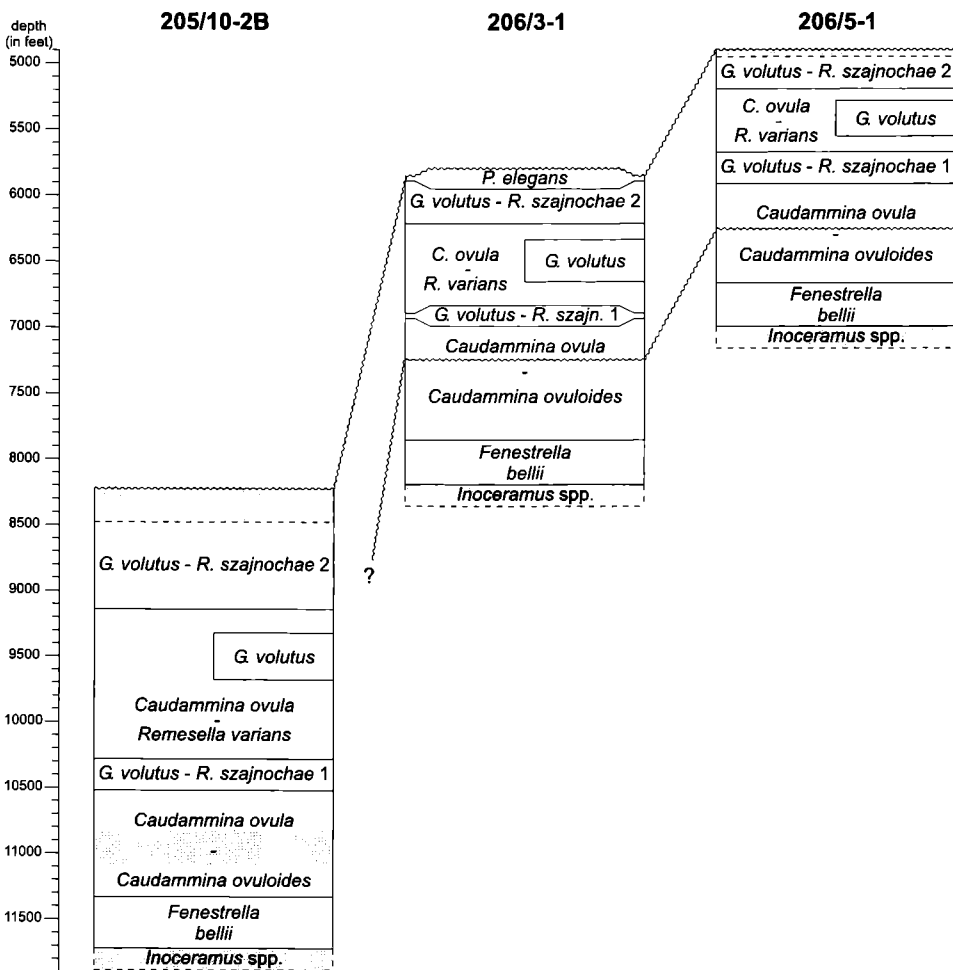


Fig. 4: Correlation of zones recognised in the three studied wells from the Foula Sub-basin. Depths of Base Paleogene unconformities (at 8223, 5890 and 4895 ft. in respectively wells 205/10-2B, 206/3-1 and 206/5-1) and mid-Campanian unconformity (at 7240 and 6250 ft. in respectively wells 206/3-1 and 206/5-1) are taken from the lithostratigraphy. Grey shadings indicate intervals which are not studied.

formity is very distinct and Paleocene assemblages are easily differentiated from Maastri-
 trichtian assemblages.

The composition of the assemblage is similar to the previous described zone, apart
 from the presence of the planktonic foraminiferal taxa *Pseudotextularia elegans* and
Planoglobulina acervulinoides.

5. DISCUSSION

5.1. Correlation

The distribution of the above described zones in the Foula Sub-basin is indicated by
 correlation between the three studied wells (see Fig. 4). All the zones are present in the
 studied sections, apart from the *P. elegans* Range Zone which is only present in well
 206/3-1. One striking feature is the increase in thickness of the interval from well 206/
 5-1 (which is closest to the margin of the Faeroe-Shetland Basin) towards well 205/10-
 2B. This indicates that the main depocentre of the Faeroe-Shetland Basin during the Late
 Cretaceous was located to the NW of the Flett Ridge. In the lower part of the studied
 sections (*F. bellii* Range Zone to *G. volutus* – *R. szajnochae* 1 Acme Zone) the relative
 thickness between the wells does not differ much, suggesting a similar sedimentation
 rate. In the upper part of the sections (from *C. ovula* – *R. varians* Partial-range Zone to
P. elegans Range Zone) the sedimentation rate increases; this is most obvious in well
 205/10-2B.

The zonation scheme proposed for the Foula Sub-basin displays many features in
 common with other studied sections on the Northeast Atlantic margin, although there

my	AGE	western Tethys Zonation of KUHNT et al. (1992)	Zumaya Zonation of KUHNT & KAMINSKI (1997)	Foula Sub-basin Zonation, this study	northern North Sea Basin FCN Zonation of KING et al. (1989)	Norwegian margin Zonation of GRADSTEIN et al. (1999)
65	MAASTRICHTIAN	late <i>Remesella variens</i>	<i>Remesella variens</i>	hiatus	21 b <i>P. elegans</i>	<i>Pseudotextularia elegans</i>
				<i>G. volutus</i> - <i>R. szajnochae</i> 2	a <i>Rugoglobigerina</i> spp.	
				<i>G. volutus</i>	d <i>Reussella szajnochae</i>	
70	early		<i>Caudammina ovula/gigantea</i>	<i>Caudammina ovula</i>	20 b-cA non-calcareous agglutinants	<i>Reussella szajnochae</i>
				<i>Remesella varians</i>	a	
75	late	<i>Homosina gigantea</i>		<i>Reussella szajnochae</i> 1	19	<i>Tritaxia capitosa</i>
				<i>Globigerinelloides volutus</i>		
80	mid			<i>Caudammina ovula</i>	18	unnamed (non-calcareous agglutinated foraminifera)
				<i>Caudammina ovuloides</i>		
85	early	<i>Goessella rugosa</i>	<i>Goessella rugosa</i>	<i>Fenestrella bellii</i>	17	radiolana
85	SANTONIAN	<i>Uvigerinammina jankoi</i>	<i>Uvigerinammina jankoi</i> (partly)	<i>Inoceramus</i> spp.	16	<i>S. granulata polonica</i>
						<i>S. granulata polonica</i>

Fig. 5: Comparison of the zonation from the Foula Sub-basin (this study), with the succession of
 zones proposed for the Western Tethys, Zumaya (Spain), the northern North Sea Basin and
 the Norwegian margin (KING et al., 1989; KUHNT et al., 1992; KUHNT & KAMINSKI, 1997;
 GRADSTEIN et al., 1999). Timescale is after GRADSTEIN & OGG (1996).

are notable local differences. In Fig. 5 the zonation schemes of five study areas are arranged from south to north for comparison. This study of the Foula Sub-basin provides an important link between the southern and northern regions of the North Atlantic. For the zonations of the North Sea Basin (KING et al., 1989), this study of the Foula Sub-basin and the Norwegian margin (GRADSTEIN et al., 1999), only last occurrence events of the index species (which include benthic and planktonic foraminifera, and siliceous microfossils) are considered, whereas for the definition of zones in the Western Tethys (KUHNT et al., 1992; KUHNT & KAMINSKI, 1997), both last and first occurrences of only agglutinated taxa are used.

In the Western Tethys, *Goesella rugosa* is the index species for the lower to middle Campanian. Further north, in the Foula Sub-basin and North Sea Basin, only a few specimens of *G. rugosa* have been recovered; therefore, alternative criteria are used for correlation in these northern Northeast Atlantic margins for this interval. Furthermore, in the Foula Sub-basin only few of the *Caudammina* specimens could be assigned to the large species *Caudammina gigantea*, while in the northern North Sea Basin and Norwegian margin it is absent. In these more northern parts on the Northeast Atlantic margin the related, though smaller species *Caudammina ovula* is the common form. *C. gigantea* is characteristic of a lower bathyal to abyssal environment, reported from the Carpathians (GEROCH & NOWAK, 1984; NEAGU, 1990) and Western Tethys (MOULLADE et al., 1988; KUHNT, 1990; KUHNT & KAMINSKI, 1990). The palaeobiogeographic distribution of both taxa *G. rugosa* and *C. gigantea* suggests these can be regarded as predominantly Tethyan related species. The consistent occurrence of *Remesella varians* in all five studied areas makes it a reliable index species for the Maastrichtian of the North Atlantic margin, although its occurrence might be limited in places by calcite dissolution (it is a calcite cemented agglutinated taxon).

The Campanian to Maastrichtian biostratigraphy of the Foula Sub-basin is most closely related to the northern areas on the North Atlantic margin. Because of the long ranges of the taxa *C. ovula* and *R. varians*, other microfossil events are used for correlation in these northern areas. The presence of Tethyan related species in the Foula Sub-basin, although in much lower abundance, indicates the transitional character of its microfauna between the Tethyan realm in the south and the Boreal realm in the north.

5.2. Unconformities

In the proposed zonation scheme for the Foula Sub-basin, two unconformities are indicated (see Fig. 3). The first one is the unconformity during the mid Campanian, which is derived from studied seismic data. In seismic sections, the Campanian to Maastrichtian succession of mudstones is a transparent interval, apart from a single distinctive reflection. This horizon represents an angular unconformity, with subsequent reflections downlapping on this level. The reflection of this unconformity can be traced in many places in the Foula Sub-basin, although in the area of the Flett Ridge and further to the north-west, this reflection is no longer clearly observed. From the literature, this unconformity is reported to be most clearly observed in the West Shetland Basin (see Fig. 1 for location; RIDD, 1981; HITCHEN & RITCHIE, 1987), although it is also reported from parts of the Foula Sub-basin (HITCHEN & RITCHIE, 1987). The event is related to a pulse of slight uplift of the Rona Ridge along the Rona Fault (RIDD, 1981; DEAN et al., 1999),

resulting in some erosion. In the Foula Sub-basin, the angular unconformity is not the result of active erosion. It represents a period of tectonically induced deepening of the basin, with little or no deposition taking place. After the tectonic event, the basin gradually filled in again with deep marine mudstones downlapping on the basin floor. The seismic reflection of the unconformity is clearly observed in seismic sections across wells 206/3-1 and 206/5-1, while in the area of well 205/10-2B the reflection becomes weak or is poorly developed, possibly obscured by the presence of dolerite intrusions (in the interval 10820–11090 ft.). After conversion to well log depth in wells 206/3-1 and 206/5-1, it appears that this level is only characterised by small well log transitions. Correlation of the unconformity depths with the biozonation scheme (see Fig. 3) indicates that the event of uplift of the Rona Ridge took place during the late part of the *Caudammina ovula* – *Caudammina ovuloides* Partial-range Zone, which suggests a mid Campanian age of the event.

The unconformity which marks the upper boundary of the Maastrichtian mudstones is an erosional surface. Throughout the Foula Sub-basin this Base Paleogene unconformity is recognised in well logs, seismic sections, and it is also characterised by a distinct faunal turnover. The event is related to thermal doming, associated with the development of the Icelandic mantle plume (EBDON et al., 1995; NADIN et al., 1997). During the early Paleocene, the thermally induced uplift caused regional extension in the Faeroe-Shetland Basin. 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 Faeroe-Shetland Basin (EARLE et al., 1989). The Rona Ridge acted as the shelf edge from where submarine fans prograded into deeper parts of the basin (KNOTT et al., 1993). The early Paleocene uplift of the West Shetland Platform and Basin also led to erosion in large parts of the Foula Sub-basin. This erosional event truncated the Maastrichtian mudstones to various depths. In well 206/3-1 sediments of the latest Maastrichtian *Pseudotextularia elegans* Range Zone are still present, whereas in wells 205/10-2B and 206/5-1 the top of the late Maastrichtian *Globigerinelloides volutus* – *Reussella szajnochae* 2 Acme Zone is also eroded (see Fig. 4). So, in the Foula Sub-basin the Base Paleogene erosional event resulted in an hiatus encompassing upper Maastrichtian and lower Paleocene sediments. In parts of the basin closest to the Rona Ridge (e.g. wells 206/3-1 and 206/5-1), occasional renewed uplift and erosion events took place during late Paleocene, and upper Paleocene sediments rest unconformably on upper Maastrichtian sediments.

6. SUMMARY

In this study, ditch cuttings of three wells from the Foula Sub-basin were analysed for microfossils. Based on the succession of these microfossils (including abundant and diverse agglutinated foraminifera, calcareous benthic and planktonic foraminifera, diatoms and radiolarians), a biozonation scheme for the Campanian to Maastrichtian interval is proposed. The scheme consists of six zones: *Pseudotextularia elegans* Range Zone (latest Maastrichtian), *Globigerinelloides volutus* – *Reussella szajnochae* 2 Acme Zone (late Maastrichtian), *Caudammina ovula* – *Remesella varians* Partial-range Zone (early and late Maastrichtian), *Globigerinelloides volutus* – *Reussella szajnochae* 1 Acme

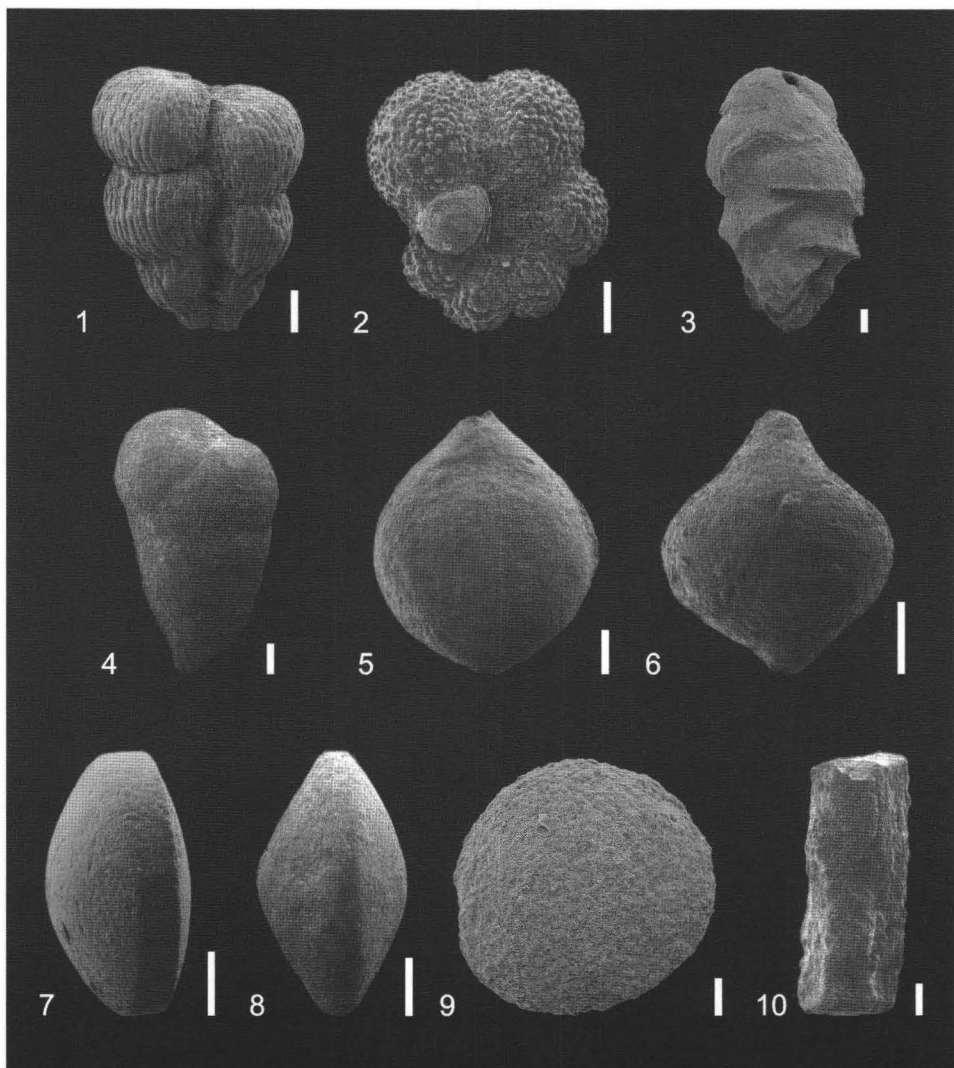
Zone (late Campanian), *Caudammina ovula* – *Caudammina ovuloides* Partial-range Zone (mid Campanian) and *Fenestrella bellii* Range Zone (early Campanian). The biostratigraphy of the Foula Sub-basin correlates best with the biostratigraphy of the North Sea Basin and Norwegian margin. However, the presence of Tethyan related species, although in much lower abundance, indicates the transitional character of its microfauna between the Tethyan realm in the south and the Boreal realm in the north. The biostratigraphy also provides constraints about the timing and extent of the unconformities in the Foula Sub-basin. Uplift of the Rona Ridge during the mid Campanian resulted in a period of accelerated deepening of the Foula Sub-basin with little or no deposition taking place. This event is characterised by an angular unconformity. During the early Paleocene, the area west of the Shetland Islands was subjected to thermal doming, causing regional uplift. This resulted in a widespread Base Paleogene unconformity which is characterised by a hiatus encompassing upper Maastrichtian and lower Paleocene sediments.

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Plate 1

Index taxa from the Foula Sub-basin. Length of scale bar: 100 μm for Figs. 1, 2, 5 and 6; 50 μm for Figs. 3, 4, 7–10.

- Fig. 1: *Pseudotextularia elegans* (RZEHAKE); sample 205/10-2B: 7820 ft.
- Fig. 2: *Globigerinelloides volutus* WHITE; side view of specimen with double terminal chambers present, sample 206/5-1: 5220 ft.
- Fig. 3: *Reussella szajnochae* (GRZYBOWSKI); sample 206/5-1: 5400 ft.
- Fig. 4: *Remesella varians* (GLAESSNER); sample 205/10-2B: 10040 ft.
- Fig. 5: *Caudammina ovula* (GRZYBOWSKI); sample 205/10-2B: 9920 ft.
- Fig. 6: *Caudammina ovuloides* (GRZYBOWSKI); sample 205/10-2B: 9380 ft.
- Fig. 7: diatom sp. 1; sample 206/5-1: 5700 ft.
- Fig. 8: *Fenestrella bellii* GRADSTEIN & KAMINSKI; edge view, sample 205/10-2B: 11390 ft.
- Fig. 9: big spherical siliceous radiolarian; sample 205/10-2B: 11690 ft.
- Fig. 10: *Inoceramus* spp. shell fragment; sample 205/10-2B: 11720 ft.



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