

## A Late Palaeocene–Early Eocene benthic foraminiferal record from Bovlstrup, Denmark, showing a remarkable agglutinated fauna

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**ABSTRACT** – The Bovlstrup well, Denmark, provides a detailed record of benthic foraminifera from the Upper Palaeocene and Lower Eocene deposits. The investigated interval spans four litho-units: an informal Grey Clay unit, the Holmehus Formation, the Ølst Formation and the Røsnæs Clay Formation (Danian?–Ypresian). Five interval zones based on benthic foraminifera have been established. Three of these zones (Zones 2, 3, and 4) contain exclusively agglutinated faunas. No foraminifera have previously been found in the Ølst Formation (Late Thanetian–Early Ypresian), but at Bovlstrup the formation contains a remarkable low-diversity agglutinated fauna (Zone 4). A programme of relatively dense sampling yielded information that may be lost in commercial oil well analysis. The five foraminiferal zones at Bovlstrup are correlated to established North Sea zonations, and the recognition of the faunas of Zones 3 and 4 leads to the conclusion that the zonation of King (In: Jenkins, D. G. & Murray, J. W. (Eds), *Stratigraphical Atlas of Fossil Foraminifera*, Ellis Horwood, 1989) can be refined.

The benthic faunas indicate changes in the bottom environment both at the sea floor and within the overlying water mass. A transition from a calcareous fauna to an agglutinated fauna is interpreted as the result of a change from a neutral to a slightly acidic environment at the sea floor. There is a fluctuation in water depth through the studied section with a minimum water depth during the Thanetian and Early Ypresian. Volcanic ash layers in the Ølst Formation presumably resulted in low pH values, thereby causing the extreme low diversity of the benthic foraminiferal faunas. *J. Micropalaeontol.* 16(1): 19–29, May 1997.

### INTRODUCTION

This paper presents the results of an investigation of Upper Palaeocene to Lower Eocene foraminiferal faunas of the Bovlstrup well, East Jutland, Denmark (Fig. 1). Previous studies on the foraminiferal stratigraphy of the Upper Palaeocene–Lower Eocene sediments in Denmark (Franke, 1927; Berggren, 1960a,b; Hofker, 1966; Hansen & Andersen, 1966; Hansen, 1968; Dinesen, 1972; Petersen & Buch, 1973; Dinesen *et al.*, 1977; Larsen & Jørgensen, 1977), have concentrated on the calcareous foraminifera from this time interval. The agglutinated foraminifera remain very poorly documented and are mentioned only by King (1994a, b). The Bovlstrup sequence, however, possesses relatively large numbers of agglutinated foraminifera, and the purpose of this paper is to document this rich arenaceous fauna. Three zones comprising exclusively agglutinated faunas have been established, including the first record of foraminifera from the Ølst Formation close to the Palaeocene–Eocene boundary. The faunas of the Bovlstrup well are described and correlated below and any possible connection between the faunas and the lithological formations are assessed.

The well site at Bovlstrup (Fig. 1) is approximately 50 m above sea level and the investigated section from 133 to 212 m depth below surface (See Fig. 2) includes a sequence of lithological units which represent different marine environments. The litho-units are, in ascending order: an informal Grey Clay unit, the Holmehus Formation, the Ølst Formation and the Røsnæs Clay Formation. The lithological units in the section are widely distributed in Denmark and are comprehensively described by Heilmann-Clausen *et al.* (1985). They are equivalent to the Våle Formation (or

Maureen Formation equivalent), Lista, Sele/Balder Formations and the lower part of Horda Formation respectively (see Fig. 3b) (see also Isaksen & Tonstad, 1989; Knox & Cordey, 1992; O'Connor & Walker 1993; King, 1994a). The depth of the formation boundaries at Bovlstrup are indicated on Fig. 2. The precise location of the boundary between the Holmehus and Ølst Formation is uncertain in the Bovlstrup well (drawn as a diagonal) as the sediments are not characteristic of any of the formations.

### MATERIAL AND METHODS

A total of 53 ditch cuttings samples were prepared for foraminiferal analysis at an average 1 m spacing between 180 and 212 m, although spacing was variable (1–4 m) between 133 and 178 m. The samples were washed through two sieves with mesh diameters of 0.1 and 1.0 mm, and the fraction between 0.1 and 1.0 mm was examined. To avoid the formation of acidic solutions and the disintegration of the agglutinated foraminifera, a peptisizing agent (Na<sub>4</sub>P<sub>2</sub>O<sub>7</sub> · 10H<sub>2</sub>O) was used to disintegrate the sediments instead of hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>). Where possible, at least 300 specimens were counted. In samples with few foraminifera the entire content was counted.

In order to solve some of the taxonomic problems, the internal structure of some agglutinated species excluding those that were pyritized were studied after staining with methyl violet: the specimens were soaked in methyl violet dissolved in anisole. When the colour was absorbed by the test, they were dried and placed in uncoloured anisole. The colour slowly disappeared until only the chambers remained stained. After drying, the internal structures of the chambers

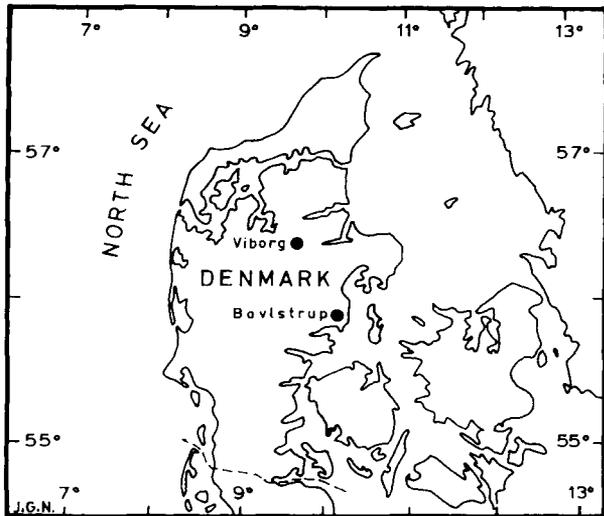


Fig. 1. Map of Denmark showing location of the Bovlstrup well and the Viborg well.

could be studied in transmitted light using a fresh drop of anisole.

Sedimentological descriptions (see Fig. 3b) and the division into litho-units were performed by Heilmann-Clausen in accordance with his definitions of the units (Heilmann-Clausen *et al.*, 1985).

Six samples were analyzed for their content of dinoflagellates by C. Heilmann-Clausen and referred to his zonation of the Viborg 1 borehole (Heilmann-Clausen, 1985).

### BENTHIC FORAMINIFERAL ZONATION AND PALAEOECOLOGY

The examined part of the Bovlstrup well has been subdivided into 5 interval zones and 3 subzones (Fig. 3a) according to the definition of Hedberg (1976). The faunal characteristics are described in ascending stratigraphic order in spite of the fact that the samples are ditch cuttings. Ecological information given by Murray (1971, 1991) and Charnock & Jones (1990) about genera and extant species is used as the basis for the present palaeoecological interpretations, with the proviso that the ecological requirements of the taxa remained unchanged in the intervening time.

#### Zone 1: The *Eponides* sp. 2–*Bathysiphon* ex. gr. *discreta* Zone

The zone consists of a single sample (212 m below surface) (Fig. 3a) of grey calcareous clay, and belongs to the informal Grey Clay litho-unit (Heilmann-Clausen *et al.*, 1985). The lithological character, the foraminiferal content and the age suggest that this is an equivalent to the Våle Formation (or 'Maureen Formation equivalent') identifiable in the Danish and Norwegian sectors of the North Sea (Isaksen & Tonstad, 1989; Knox & Cordey, 1992; O'Connor & Walker, 1993).

The benthic fauna is characterized by the presence of low

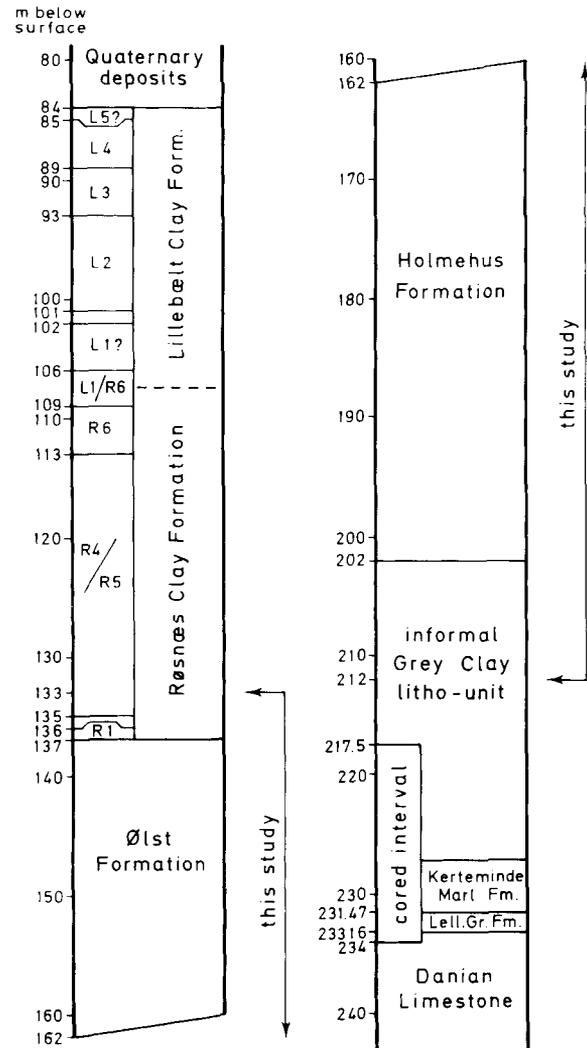


Fig. 2. The lithostratigraphy of the Bovlstrup well showing the investigated section. After Heilmann-Clausen (pers. comm., 1993).

numbers of both agglutinated and calcareous species and only 77 specimens were encountered in 100 g of sediment. This zone is characterized by the occurrence of *Eponides* sp. 2 and by *Bathysiphon* ex. gr. *discreta*, *Usbekistania charoides*, *Eponides lunatus*, *Lenticulina platypleura*, *Anomalinooides rubiginosus*, *Bulimina midwayensis* and *Haplophragmoides eggeri*.

The species composition (*Bulimina midwayensis*, *Eponides lunatus* and *Anomalinooides rubiginosus*, *Bathysiphon* ex. gr. *discreta* and *Usbekistania charoides*) together with the presence of planktic foraminifera *Eoglobigerinella* spp. (6% of total fauna) indicate an upper to middle bathyal palaeoenvironment (van Morkhoven *et al.*, 1986; Jones & Charnock, 1985)

#### Zone 2: The *Usbekistania charoides*–*Spiroplectammina spectabilis*–*Haplophragmoides* sp. 1 Zone.

Zone 2 is subdivided into three subzones: 2A (211–189 mbs), 2B (188–182 mbs) and 2C (181–162 mbs). The

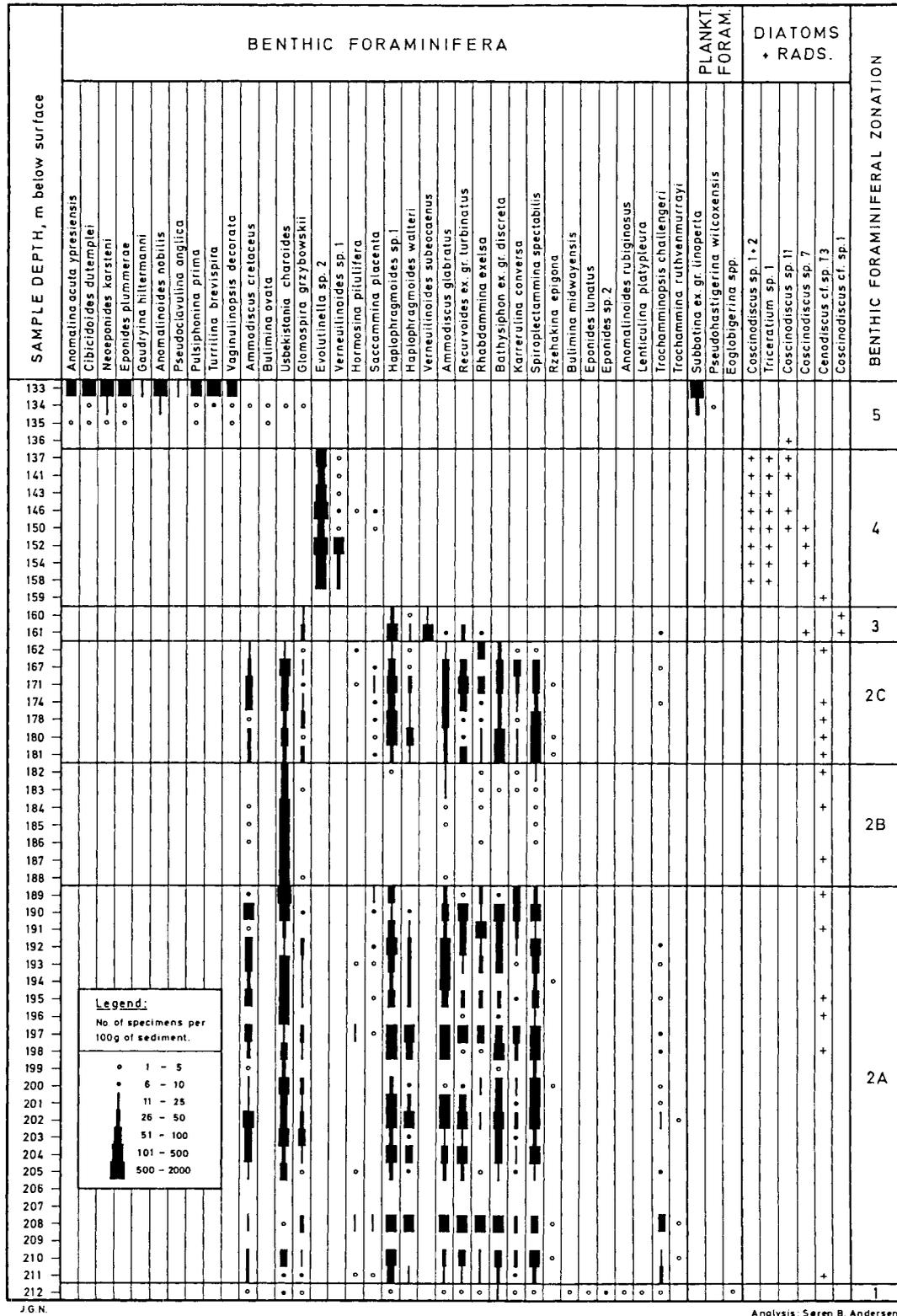


Fig. 3a. Range chart of selected species from the Bovlstrup well.

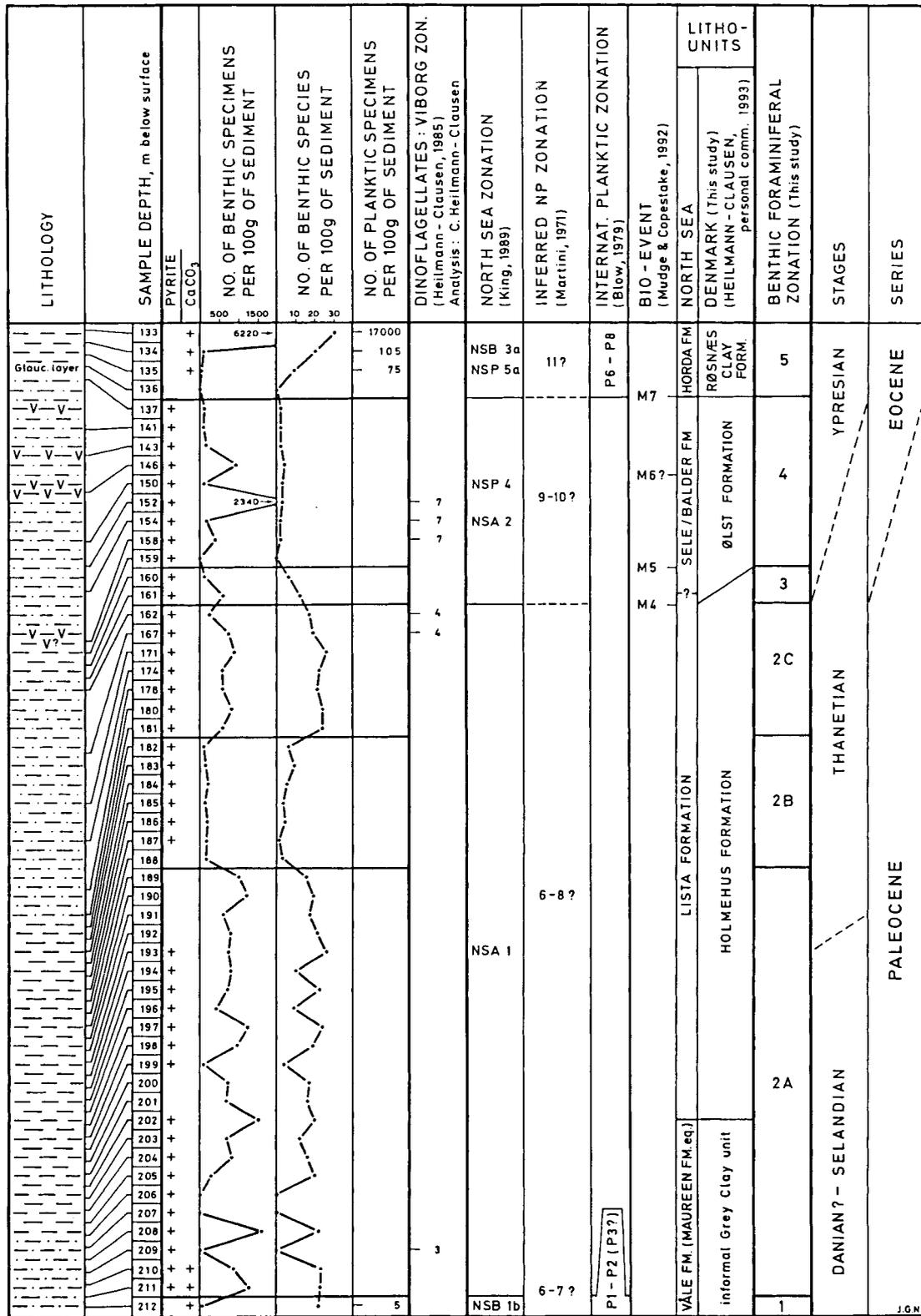


Fig. 3b. Correlation scheme of biostratigraphy and lithostratigraphy. The dinoflagellate zonation refers to samples provisionally examined by Heilmann-Clausen. The zones were originally established for the Viborg boring (Heilmann-Clausen, 1985).

lower part of Subzone 2A consists of a grey clayey sediment and is part of the informal Grey Clay litho-unit (Våle Formation equivalent). The remaining part of Zone 2 comprises green–grey clay belonging to the Holmehus Formation (Fig. 3b), which is equivalent to the Lista Formation in the North Sea (King, 1994a).

Zone 2 is easily distinguished from Zone 1 by its foraminiferal fauna of exclusively agglutinated species (Fig. 3a). The lower boundary of Zone 2 is defined by the disappearance of all calcareous taxa. The faunas in Subzone 2A and 2C are practically identical and are characterized by relatively high foraminiferal concentrations. *Usbekistania charoides*, *Haplophragmoides* sp. 1, *Ammodiscus glabratus* and *Spiroplectammina spectabilis* dominate the fauna. *S. spectabilis* disappears at the top of Zone 2. *Bathysiphon* ex. gr. *discreta*, *Recurvoides* ex. gr. *turbinatus* and *Ammodiscus cretaceus* are dominant in some of the samples but fluctuate in their occurrences. *Trochamminopsis challengerii* and *Rzehakina epigona* are characteristic species in Subzones 2A and 2C. *Trochammina ruthvenmurrayi* is only registered in the lowermost part of Subzone 2A.

Subzone 2B differs from Subzones 2A and 2C by its extremely low species diversity (Fig. 3b). The fauna in Subzone 2B is totally dominated by *Usbekistania charoides*, while *Ammodiscus cretaceus*, *Rhabdammina exelsa* and *Spiroplectammina spectabilis* occur only sporadically.

*Cenodiscus* cf. sp. T3 is found throughout Zone 2 except from the lowermost part of Subzone 2A.

The occurrence of *Rhabdammina*, *Usbekistania*, *Rzehakina*, *Bathysiphon* and *Spiroplectammina* indicate that Zone 2 was deposited in a middle to lower bathyal palaeoenvironment (Jones & Charnock, 1985; Jones, 1988; Murray, 1991). Similar agglutinated foraminiferal assemblages have been considered as indicators of reduced water circulation with low oxygen and high CO<sub>2</sub> levels at the sediment/water interface (Gradstein & Berggren, 1981; Gradstein *et al.*, 1992). However, a very low content of organic material (0.3–0.5%; H. Skovbjerg, pers. comm., 1988) and *Zoophycos* burrows in the large cuttings from the Holmehus Formation (also seen in outcrops; Heilmann-Clausen, 1989) are observed at Bøvlstrup. These observations suggest that the bottom waters were moderately to well oxygenated as indicated by Heilmann-Clausen *et al.* (1985). A possible explanation to this paradox, could be that pH was slightly below 7.8 as a result of an increased CO<sub>2</sub> content through decomposition of organic matter in sinking particles (Moorkens, 1975; Boyle, 1988). This situation would favour the removal of the CaCO<sub>3</sub> and most of the organic matter although the bottom waters would still be moderately oxygenated, sufficient for the burrowing organisms to live. The removal of CaCO<sub>3</sub> could also explain the sudden change from a calcareous fauna to an exclusively agglutinated fauna at the lower zonal boundary.

The Subzone 2B assemblage is apparently the result of secondary dissolution where only strongly cemented species are preserved. However, some aberrant specimens of *Spiroplectammina spectabilis* and *Haplophragmoides* sp. 1 are observed at the boundary between Subzone 2A and Subzone 2B. These species are smaller in size than in

Subzones 2A and 2C, while *Usbekistania charoides* is larger. This is interpreted as a result of deteriorated living conditions for the foraminifera in Subzone 2B compared to the rest of Zone 2.

### **Zone 3: The *Verneuilinoides subeoceanus*–*Haplophragmoides* sp. 1 Zone**

The zone was identified in two samples (161–160 mbs) of dark grey–green clay with a bluish tint and occurs at the transition between typical sediments of the Holmehus Formation and the Ølst Formation (Fig. 3b). As the sediments are not typical for any of the formations the location of the formation boundaries are uncertain (Figs 2 and 3b).

Coarse-grained volcanic ash was identified in the sample at 161 m (J. Eiríksson, pers. comm., 1993). At 160 m a peak in the K-curve of the gamma-ray log (Korsbech & Nielsen, 1989) indicates the presence of a glauconite layer corresponding to the glauconite horizon, which is normally observed at the base of the Ølst Formation (Heilmann-Clausen *et al.*, 1985).

The lower boundary of the zone is characterized by the change to dominance of *Verneuilinoides subeoceanus* (restricted to this zone) and *Haplophragmoides* sp. 1 (Fig. 3a). Another typical species in the zone is *Haplophragmoides walteri*. The diversity is lower than in Zone 2. The diatom *Coscinodiscus* cf. sp. 1 is restricted to this zone.

The combination of *Glomospira* and *Haplophragmoides* species (Fig. 3a) suggest an outer shelf environment (cf. Jones & Charnock, 1985) while the low species diversity points to extreme bottom water conditions with unfavourable living conditions.

### **Zone 4: The *Evolutinella* sp. 2–*Verneuilinoides* sp. 1 Zone**

Zone 4 was recognized in 9 samples (159–137 mbs) of dark, almost black tuffaceous clay from the Ølst Formation (Fig. 3b). The Ølst Formation is an equivalent of the Sele and Balder Formations developed extensively in the North Sea basin (Knox & Cordey, 1992; O'Connor & Walker, 1993).

The zone is characterized by a very low number of species, and rather fluctuating concentrations (Fig. 3b). The upper and lower boundaries of the zone are marked by an abrupt change in fauna and diversity. The zone is defined by the occurrence of *Evolutinella* sp. 2 and *Verneuilinoides* sp. 1. *Evolutinella* sp. 2 dominates, attaining more than 80 % of the fauna. Accessory species are *Saccammina placenta* and *Hormosira pilulifera*. The species are coarsely agglutinated and the tests consist entirely of the dark minerals biotite and heulandite (identified by x-ray diffraction). Pyrite in-fillings of the diatoms *Coscinodiscus* sp. 1, *Coscinodiscus* sp. 2, and *Triceratium* sp. 1 are observed throughout the zone. The diatom *Coscinodiscus* sp. 7 is restricted to the lower half of the zone and *Coscinodiscus* sp. 11 to the upper half.

The Bøvlstrup well is the first site where a foraminiferal fauna has been identified in sediments belonging to the Ølst Formation. It is possible that the lack of documentation of foraminifera from the Ølst Formation is due to low sample resolution, as it is in the case of the North Sea Balder

Formation (M. Charnock, pers. comm., 1994). The very low species diversity points to an extreme palaeoenvironment. The dominance of *Evolutinella* sp. 2 may be due to a high acid content in the water column caused by frequent volcanism (ash-layers, Fig. 3b). Such a situation has been reported by Finger & Lipps (1981) from an active Antarctic volcanic caldera: faunas at a water depth of 100–150 m were dominated here by *Trochammina* species for several years after an eruption.

Pyrite and gypsum are present in the sediment and indicate depleted oxygen conditions at the sea floor. The sediment contains more particles of the silt fraction than in the underlying zones. This may be interpreted as an indication of a slight decrease in water depth, but the silt fraction also includes fine-grained ash particles (J. Eiriksson, pers. comm., 1993).

### **Zone 5: The *Eponides plummerae*–*Neoeponides karsteni* Zone**

This zone identified in 4 samples (136–133 mbs) is developed in the red clays of the Røsnæs Clay Formation (Fig. 3b). The lowermost sample in the zone has a high content of glauconite but no foraminifera are present.

The assemblage in Zone 5 is predominantly calcareous, generally very diverse and dominated by *Cibicidoides dutemplei*, *Anomalinoides nobilis*, *Neoeponides karsteni* and *Eponides plummerae*. *Turrilina brevispira*, *Gaudryina hiltermani*, *Pseudoclavulina anglica*, and the planktic species *Pseudohastigerina wilcoxensis* and *Subbotina* ex. gr. *linaperta* are also observed. Other important species are *Vaginulinopsis decorata*, *Bulimina ovata*, *Pulsiphonina prima* and *Anomalina acuta ypresiensis*. The planktic foraminifera account for up to 74% of the total fauna.

The glauconite layer observed at the base of the zone presumably indicates a brief pause in sedimentation. The succeeding sediment is red, carbonate rich, plastic clay pointing to a well oxygenated water mass. The genus composition (*Bulimina*, *Cibicidoides* and *Eponides*) indicates an outer shelf to upper bathyal palaeoenvironment (Murray, 1991). This interpretation is supported by the diverse fauna and the increasing amount of planktic foraminifera, which indicate an increasing water depth.

## **CORRELATION AND AGE**

### **Zone 1: Danian? to Selandian**

The presence of *Lenticulina platypleura*, *Anomalinoides rubiginosus*, and *Bulimina midwayensis* suggest correlation of Zone 1 with the North Sea Benthic foraminiferal zone NSB 1b of King (1989). The upper boundary of Zone 1 is sharply defined as calcareous taxa are absent in the overlying interval. This phenomenon was described by King (1989) at the upper boundary of Zone NSB 1b. An equivalent of King's NSB 1c Subzone was not identified. In addition, the co-occurrence of *Eponides lunatus* and *Lenticulina platypleura* (*L. multiformis* of Doppert & Neele, 1983) implies correlation of Zone 1 with Zone FJ from the Netherlands (Doppert & Neele, 1983).

The presence of the eoglobigerinids in the zone implies a

correlation with P1–P2 and maybe P3 of the standard planktic foraminiferal zonation of Blow (1979, p. 303, fig. 45). This indicates a Danian to Selandian age.

Slightly higher in the Bovlstrup profile (at 209 m; lower part of Subzone 2A, Fig. 3b) the presence of dinoflagellate Zone 3 of Viborg (Heilmann-Clausen, 1985; pers. comm., 1988) suggests a correlation to nannoplankton Zone NP 6–7 (Martini, 1971). This indicates a Late Selandian age (dinoflagellate Zone 3 of Viborg occurs below the Thanetian (Heilmann-Clausen pers. comm., 1993)).

### **Zone 2: Late Selandian to Thanetian**

The presence of *Spiroplectammina spectabilis*, which has its last appearance at the top of Zone 2, and *Rzehakina epigona*, *Recurvoides* ex. gr. *turbinatus*, *Bathysiphon* ex. gr. *discreta*, *Ammodiscus cretaceus* and *Karrerulina conversa* indicate a correlation of Zone 2 with Zone NSA 1 (North Sea Agglutinated) of King (1989). The Holmehus Formation has previously been assigned to Zone NSP 3 and Subzone NSB 1c equivalents of NSA 1b by King (1989, compare figs 9.3 and 9.9). The fact that *Trochammina ruthvenmurrayi* is only found in the lowermost part of the zone is in opposition to the observations of King (1989) but in agreement with those of Gradstein *et al.* (1994). Bovlstrup Zone 2 corresponds to the majority of the *Trochammina ruthvenmurrayi*–*Reticulophragmium paupera* Zone of Gradstein *et al.* (1992, 1994) and the top of Bovlstrup Zone 2 corresponds to bioevent M4 of Mudge & Copestake (1992). Bovlstrup Zone 2 differs from the corresponding offshore interval in the lack of primitive cyclamminids as found by Gradstein & Berggren (1981), Charnock & Jones (1990) and Gradstein *et al.* (1994). An influx of agglutinated species seen at the transition between Zones FJ and FI in the Dutch area (Doppert & Neele, 1983) also infers correlation to Zone 2.

The boundary between the informal Grey Clay litho-unit and the Holmehus Formation is placed at 202 m well depth as cuttings from both litho-units occur in the sample at this level (Heilmann-Clausen, pers. comm., 1988). This boundary occurs within Zone 2 in the Bovlstrup well. *Trochammina ruthvenmurrayi* is found below the lithological boundary and *Cenodiscus* cf. sp. T3 above.

A sample 3 m above the lower boundary of Zone 2 contained a Viborg Zone 3 dinoflagellate flora, and two samples from the uppermost part of Zone 2 possessed Viborg Zone 4 floras (Heilmann-Clausen, 1985; pers. comm., 1988). This implies that Zone 2 corresponds to both a part of dinoflagellate Zone 3 and probably most of Zone 4 of Viborg (Heilmann-Clausen, 1985) and to Zone NSA 1b (King, 1989). Therefore, Zone 2 of Bovlstrup can probably be referred to nannoplankton Zones NP 6–NP 8 (see also King, 1989), indicating a possible Late Selandian to Thanetian age which also is in agreement with the correlations of Gradstein *et al.* (1994).

The boundary between the Selandian and Thanetian (Fig. 3b) is tentatively placed half way between the sample yielding the Viborg Zone 3 dinoflagellate flora and the lowermost sample referred to dinoflagellate Zone 4.

### Zone 3: Thanetian

The presence of *Verneuilinoides subeocaenus* in Zone 3 and the sparse, generally poorly preserved fauna correspond to the faunal characteristics of lower part of Zone NSA 2 (King, 1989) although King did not recognize this assemblage as distinct. The NSA 2 Zone of King is correlated to his NSP 4 Zone indicated by the presence of *Coscinodiscus* sp. 1 and *Coscinodiscus* sp. 2. In Bovlstrup Zone 3, however, none of the characteristic diatoms of NSP 4 were found, but they are present in the above lying Zone 4. For this reason Bovlstrup Zone 3 is correlated with the lower part of NSA 2. The present features were probably only observed due to a close sampling interval. In a commercial oil well, where the sampling interval is commonly 10 m, a Zone 3 equivalent might easily escape sampling, and Zones 3 and 4 would accordingly be registered as one.

Gradstein *et al.* (1994, p. 37) state that the NSA 2 Zone of King (1989) is found only in the southern part of the North Sea. They find the *Coscinodiscus* assemblage but not the *Verneuilinoides subeocaenus* assemblage. As Zone 3 (characterized by *Verneuilinoides subeocaenus*) is represented only in a 2 m interval it is easy to understand why it was not found in exploration wells in the northern North Sea.

The top of Bovlstrup Zone 3 probably corresponds to bioevent M5 of Mudge & Copestake (1992) and O'Connor & Walker (1993). These authors state that the event is isochronous over large parts of the basin as it probably reflects a change in the bottom water conditions.

Unfortunately no dinoflagellate analysis were carried out in Zone 3 and the chronostratigraphic allocation of the zone is thus uncertain. Bovlstrup Zone 3 falls between samples dated using dinoflagellates to be Early Thanetian (Viborg Zone 4, Heilmann-Clausen, pers. comm.) and samples dated to Late Thanetian to Early Ypresian. We therefore suggest Zone 3 to be of Thanetian age.

### Zone 4: Late Thanetian to Early Ypresian

The faunal composition of Zone 4 (almost exclusively *Evolutinella* sp. 2 and *Verneuilinoides* sp. 1) combined with the presence of pyritized and siliceous diatoms (*Coscinodiscus* sp. 1, *Coscinodiscus* sp. 2, *Triceratium* sp.1, *Coscinodiscus* sp. 7 and *Coscinodiscus* sp. 11) are rather unique features and have not previously been registered in Denmark.

*Evolutinella* sp. 2 is found only in a very narrow time interval in the Late Palaeocene to Early Eocene (Charnock & Jones, 1990).

The first downhole occurrence of *Coscinodiscus* sp. 7 in the middle of Bovlstrup Zone 4 (sample 150 m) indicates a possible correlation with bioevent M6 of Mudge & Copestake (1992) whereas the top of Zone 4 is correlated with bioevent M7 (top *Coscinodiscus* sp. 1).

*Coscinodiscus* sp. 1 and other diatoms occur frequently in the lowermost part of the FI Zone of the Netherlands (Doppert & Neele, 1983), but the foraminiferal fauna in this interval shows no resemblance to the Bovlstrup Zone 4 fauna. Zone 4 is, nevertheless, tentatively correlated to the lowermost part of the FI Zone, to the *Coscinodiscus* Zone

of Gradstein *et al.* (1992, 1994), and to the NSP 4 Zone of King (1989) because of the presence of *Coscinodiscus* sp. 1.

Comparable foraminiferal faunas have been found in the Untereozän 1 of Germany (Wick, 1943; Bettenstaedt *et al.*, 1962) and in the basal Ieper Formation of Belgium (Willems, 1983).

Dinoflagellates were studied in three samples from Zone 4 (156, 154, and 152 mbs). The flora placed the samples in Zone 7 of Viborg and thus with the upper part of the Ølst Formation (Heilmann-Clausen, 1985, p. 30) indicating a Late Thanetian to Early Ypresian age. The dinoflagellates suggest a tentative correlation of Bovlstrup Zone 4 with nannoplankton Zones NP 9–10 of Martini (1971) (see also Gradstein *et al.*, 1994, p. 37). The formal boundary between the Palaeocene and the Eocene is not yet internationally agreed upon, but it is normally placed at, or close to the NP 9–10 boundary.

The lithological boundary between the Ølst Formation and the Røsnæs Clay Formation has been placed between 136 and 137 m below the surface (Heilmann-Clausen pers. comm., 1988).

### Zone 5: Ypresian

The presence of *Gaudryina hiltermani*, *Pseudoclavulina anglica* and *Turrilina brevispira* in Bovlstrup Zone 5 justifies a correlation with Zone NSB 3a of King (1989). This is further supported by the planktic fauna of the sample at 133 m, which is totally dominated by *Subbotina* ex. gr. *linaperta*. Zone 5 is consequently placed in Zone NSP 5a (King, 1989). Furthermore, Zone 5 equates with part of the *Subbotina patagonica* Zone of Gradstein *et al.* (1992, 1994).

The dominance of *Subbotina* ex. gr. *linaperta* and the presence of *Pseudohasterigerina wilcoxensis* indicate a correlation with P6–P8 of the standard planktic foraminiferal zonation of Blow (1979) (see also Gradstein *et al.*, 1994). The top of the acme of *Subbotina* ex. gr. *linaperta* is correlated to a position in P8 by King (1989) and Mudge & Bujak (1994). Bovlstrup Zone 5 may therefore correspond to NP 11–12. This is based on the correlation with NSP 5a (see also King, 1983) and on the fact that the Røsnæs Clay Formation has previously been correlated to NP 11–12 (Heilmann-Clausen, 1989). Zone 5 is consequently of Ypresian age.

## SUMMARY AND DISCUSSION

The Bovlstrup well provides new information on foraminiferal faunas and palaeoenvironments of upper Palaeocene and lower Eocene deposits in Denmark. Especially significant is that whereas no foraminiferal faunas have previously been encountered in the Ølst Formation, this interval in the Bovlstrup well contains a remarkable low-diversity agglutinated fauna.

### Stratigraphy

The five foraminiferal zones at Bovlstrup are readily referred to the established North Sea zonation of King (1983, 1989). Relatively dense sampling (maximum 4 m between the samples), however, yielded information that may be lost in commercial oil wells.

Zone 1 is placed in Subzone NSB 1b of King (1989) and a

Danian to Selandian age is suggested. Fluctuations in the faunal diversity in Zone 2 (Fig. 3b) formed the basis for a division into 3 subzones. These are correlated with NSA 1 Zone of King (1989) and are of Late Selandian to Thanetian age. The boundary between Selandian and Thanetian may occur in the middle of Zone 2. Zone 3 can be correlated to the lower part of Zone NSA 2 (King, 1989) but of special interest here is the absence of *Coscinodiscus* sp. 1 (the characteristic diatom of NSP 4). On the other hand, *Coscinodiscus* sp. 1 is present in Bovlstrup Zone 4, and this indicates that Zone 4, identified by high proportions of *Evolutinella* sp. 2 and by *Verneulinoides* sp. 1, also equates to Zone NSA 2. The present features are probably only observed due to the dense sampling. Bovlstrup Zone 3 is referred to Thanetian and Zone 4 to the Late Thanetian or Early Ypresian and, therefore cover the Palaeocene–Eocene boundary. Bovlstrup Zone 5 corresponds to Subzones NSB 3a and NSP 5a of King (1989) and an Ypresian age for this zone is suggested.

#### Litho-units

The foraminiferal zones of the Bovlstrup well occur in the following litho-units (Fig. 3b): Zone 1 and the lower part of Subzone 2C correlate with the informal Grey Clay litho-unit (Heilmann-Clausen *et al.*, 1985). The boundary between the Grey Clay and the Holmehus Formation may be identified biostratigraphically at Bovlstrup: *Trochammina ruthvenmurrayi* is found below the lithological boundary and *Cenodiscus* cf. sp. T3 above. The remaining part of Zone 2 corresponds to the Holmehus Formation. Zone 3 represents a transition zone between the Holmehus Formation and the Ølst Formation. Bovlstrup Zone 4 constitutes part of the Ølst Formation, probably the upper part as indicated by the dinoflagellates (Viborg Zone 7 only occurs in the upper half of the Ølst Formation, Heilmann-Clausen, 1985, p. 30). Zone 5 is correlated with the lowermost part of the Røsnæs Clay Formation.

#### Palaeoenvironment

The palaeo-water depths indicated by the foraminifera of the Bovlstrup deposits reflect the eustatic sea-level curve of Haq *et al.* (1988) and the relative sea-level curve of Michelsen *et al.* (in press): The increasing water depth from an upper to middle bathyal environment in Bovlstrup Zone 1 to middle to lower bathyal in Zone 2 are associated with the rising sea level of TA 2.1 of Haq *et al.* (1988) (sequence 1.1 of Michelsen *et al.*, in press). The condensed horizon may be observed at the lithological boundary between the informal Grey Clay unit and the Holmehus Formation as the number of specimens has a local peak at this place. This lithological boundary corresponds to the boundary between the Maureen Formation and the Lista Formation where a condensed horizon characterized by an acme of *Cenodiscus* is reported (see O'Connor & Walker, 1993). Unfortunately *Cenodiscus lenticularis* was not found in the Bovlstrup well.

The decrease in water depth from the bathyal in Bovlstrup Zone 2 to the outer shelf environment of Zone 3 (and maybe even further decrease in Zone 4) is probably associated with the sea level drop of TA 2.2 or TA 2.3 of

Haq *et al.* (1988) and the base of sequence 1.2 of Michelsen *et al.* (in press).

The increasing water depth from the shelf environment in Bovlstrup Zones 3 and 4 to the outer shelf to upper bathyal as indicated by the increasing amount of planktic foraminifera in Zone 5, may correspond to TA 2.5–2.6 of Haq *et al.* (1988) and sequence 2 of Michelsen *et al.* (in press).

The benthic faunas also indicate radical changes in the bottom water conditions. We interpret the transition from the calcareous fauna of Zone 1 to an exclusively agglutinated fauna in Zone 2 as the result of a change to a slightly acidic environment at the sea floor. The low diversity of the fauna in Zone 3 indicates that bottom water conditions may have deteriorated. The volcanic ash layers of Zone 4 presumably resulted in low pH values, leading to benthic faunas with extremely low diversities. This may correspond to the short-term negative excursion in both carbon and oxygen isotopes observed in DSDP wells worldwide at the Palaeocene–Eocene boundary (Pak & Miller, 1992, p. 419), as the CO<sub>2</sub> from the volcanism may have caused polar warming. This event led to the largest deep-water benthic foraminiferal turnover of the Cenozoic. After a pause or reduction in sedimentation, indicated by a fossil-free, glauconite-rich sample at the boundary between Bovlstrup Zones 4 and 5, the oceanographic setting changed dramatically to one of improved water circulation with oxygenated bottom waters.

#### CHECKLIST OF TAXA

##### Foraminifera

- Ammodiscus cretaceus* (Reuss, 1845)
- Ammodiscus glabratus* Cushman & Jarvis, 1928
- Anomalina acuta ypresiensis* (ten Dam, 1944)
- Anomalinoidea nobilis* Brotzen, 1948
- Anomalinoidea rubiginosus* (Cushman, 1926)
- Bathysiphon* ex. gr. *discreta* (Brady, 1881)
- Bulimina ovata* d'Orbigny, 1846
- Bulimina midwayensis* Cushman & Parker, 1936
- Cibicidoides dutemplei* (d'Orbigny, 1846)
- Eoglobigerina* spp.
- Eponides lunatus* Brotzen, 1948
- Eponides plummerae* Cushman, 1948
- Eponides* sp. 2
- Evolutinella* sp. 2 Charnock & Jones, 1990
- Gaudryina hiltermani* Meisl, 1959
- Glomospira grzybowskii* Jurkiewicz, 1960
- Haplophragmoides* sp. 1 Charnock & Jones, 1990
- Haplophragmoides walteri* (Grzybowski, 1898)
- Hormosina pilulifera* Brady, 1884
- Karrerulina conversa* (Grzybowski, 1901)
- Lenticulina platypleura* (Jones, 1852)
- Neoeponides karsteni* (Reuss, 1855)
- Pseudoclavulina anglica* (Cushman, 1936)
- Pseudohastigerina wilcoxensis* Cushman & Ponton, 1932
- Pulsiphonina prima* (Plummer, 1926)
- Recurvovoides* ex. gr. *turbinatus* (Grzybowski, 1898)
- Rhabdammina exelsa* Grzybowski, 1898
- Rzehakina epigona* (Rzehak, 1895)

*Saccamina placenta* (Grzybowski, 1898)  
*Spiroplectamina spectabilis* (Grzybowski, 1898)  
*Subbotina* ex. gr. *linaperta* (Finlay, 1939)  
*Turrilina brevispira* ten Dam, 1944  
*Trochammina ruthvenmurrayi* Cushman & Renz, 1946  
*Trochamminopsis challengeri* (Brönnimann & Whittaker, 1988)  
*Vaginulinopsis decorata* (Reuss, 1855)  
*Verneulinoides* sp. 1  
*Verneulinoides subeoceanus* (Wick, 1943)  
*Usbekistania charoides* (Jones & Parker, 1860)

*Verneulinoides* sp. 1

(Pl. 1, Fig. 20)

*Verneulinoides* sp. 1 resembles *Verneulinoides subeoceanus* (Wick) but is more coarsely agglutinated. *Verneulinoides* sp. 1 is twisted 90° around its own axis and has a more pronounced triserial arrangement than *Verneulinoides subeoceanus*.

*Eponides* sp. 2

*Eponides* sp. 2 resembles *Eponides lunatus* (Brotzen) but lacks distinct sutures and pores. *Eponides* sp. 2 has a central depression on the umbilical side.

#### Diatoms

*Coscinodiscus* sp. 1 Bettenstaedt *et al.*, 1962

*Coscinodiscus* sp. 2 Bettenstaedt *et al.*, 1962

*Coscinodiscus* sp. 7 RRI

*Coscinodiscus* sp. 11 RRI

*Coscinodiscus* cf. sp. RRI

*Triceratium* sp. 1 Bettenstaedt *et al.*, 1962

#### Radiolarians

*Cenodiscus* cf. sp. T3 RRI

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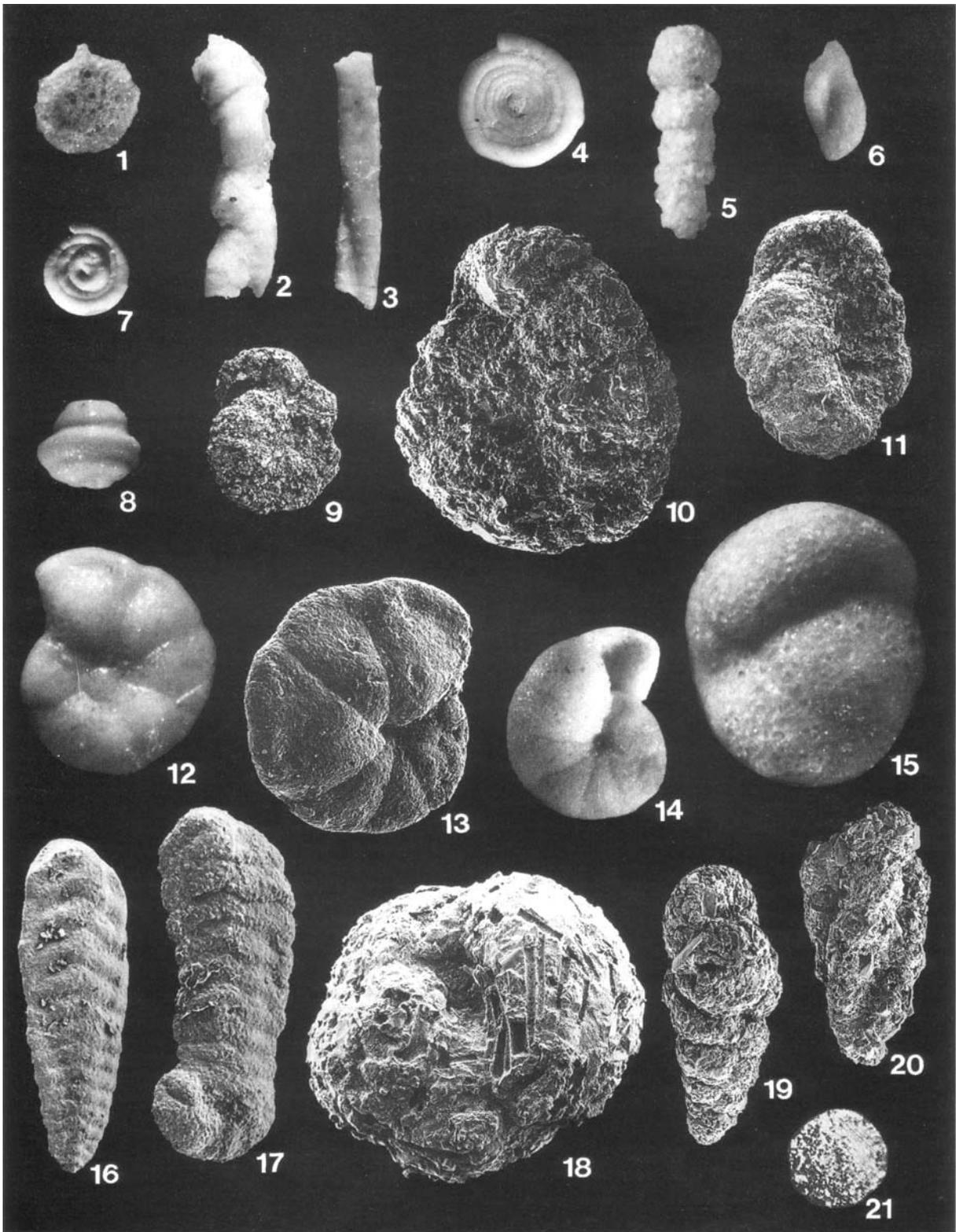


Plate 1

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#### Explanation of Plate 1

**Fig. 1.** *Saccanmina placenta*, sample 197,  $\times 60$ . **Fig. 2.** *Rhabdammina exelsa*, sample 198,  $\times 37.5$ . **Fig. 3.** *Bathysiphon* ex. gr. *discreta*, sample 208,  $\times 37.5$ . **Fig. 4.** *Ammodiscus cretaceus*, sample 208,  $\times 37.5$ . **Fig. 5.** *Hormosina pilulifera*, sample 197,  $\times 60$ . **Fig. 6.** *Rzehakina epigona*, sample 200,  $\times 60$ . **Fig. 7.** *Glomospira grzybowskii*, sample 198,  $\times 37.5$ . **Fig. 8.** *Usbekistania charoides*, sample 187,  $\times 60$ . **Fig. 9.** *Evolutinella* sp. 2, sample 146, SEM  $\times 40$ . **Fig. 10.** *Evolutinella* sp. 2, sample 146, SEM  $\times 90$ . **Fig. 11.** *Evolutinella* sp. 2, sample 146, SEM  $\times 60$ . **Fig. 12.** *Haplophragmoides walteri*, sample 198,  $\times 60$ . **Fig. 13.** *Haplophragmoides walteri*, sample 198, SEM  $\times 130$ . **Fig. 14.** *Haplophragmoides* sp. 1, sample 198,  $\times 60$ . **Fig. 15.** *Recurvoides* ex. gr. *turbinatus*, sample 195,  $\times 60$ . **Fig. 16.** *Spiroplectamina spectabilis*, microspheric, sample 200, SEM  $\times 60$ . **Fig. 17.** *Spiroplectamina spectabilis*, megalospheric, sample 200, SEM  $\times 70$ . **Fig. 18.** *Trochamminopsis challengerii*, sample 208, SEM  $\times 80$ . **Fig. 19.** *Verneulinoides subeocaenus*, sample 161, SEM  $\times 80$ . **Fig. 20.** *Verneulinoides* sp. 1, sample 158, SEM  $\times 85$ . **Fig. 21.** *Coscinodiscus* cf. sp. 1, sample 161,  $\times 67$ .