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DETAILED FORAMINIFERAL BIOSTRATIGRAPHY OF MIOCENE FORMATIONS IN DENMARK

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Miocene strata penetrated in eighteen boreholes in Denmark have been studied for their foraminiferal contents. The dense sampling used (intervals of approximately 0.5 m) has allowed a very detailed biozonation to be established. Some of the boreholes have been analysed in detail, while others have just scanned for similarities in faunal patterns. It has proved possible in the present study to apply the established North Sea benthic and planktic foraminiferal zonations. As a result of the dense sampling used here, some of these zones can now be further subdivided. Additionally, a number of substitute marker species are presented here for both the benthic and planktic zonations. A correlation between biostratigraphic zones and lithostratigraphic units is presented. The data demonstrate the occurrence of several oscillations in water depth during the Miocene; an attempt is made to correlate these with the sequence-stratigraphic framework for the Danish North Sea area.

Key words — Miocene, Denmark, Foraminifera, biostratigraphy.

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INTRODUCTION

Numerous geologists have shown an interest in the alternating marine/non-marine strata of the Miocene in Denmark. Forchhammer (1828) was the first to draw attention to this subject; he described the marine 'Mica Clay' from Morsum Cliff (Isle of Sylt, now German territory), and the non-marine 'Lignite Formation' in western Denmark (Forchhammer, 1835). Ravn (1907, 1928) subdivided this sequence into lower, middle, and upper Miocene deposits.

The Miocene formations of Denmark, occurring only in Jylland, were formally defined or described by Sorgenfrei (1940, 1958a) and Rasmussen (1956, 1961) (Table 1). Their work resulted in the classic interpretation of the distribution of marine and non-marine Miocene formations, shown here in Fig. 1. Both Sorgenfrei and Rasmussen presented detailed data on the molluscan faunas of these deposits, while Kristoffersen (1972, 1973) gave a brief overview of their foraminiferal contents. Dinoflagellate cysts from the Hodde (Middle Miocene) and Gram (Middle-Late Miocene) formations were studied by Piasecki (1980), while a combined biostratigraphic analysis of the Arnum, Hodde and Gram formations has recently been published by Laursen *et al.* (1998).

The present study was initiated in the early 1970s, when the wells presented here were first analysed by one of us (Kristoffersen, 1972, 1973; see also Bertelsen & Kristoffersen, 1974). Here, this work is reanalysed and supplemented by additional studies. Preliminary results were presented by Laursen & Kristoffersen (1995).

FORMATION	DEFINED OR DESCRIBED BY	LITHOLOGY
"Sæd" (Brackish-marine)	Sorgenfrei (1958b), Rasmussen (1958)	Greybrown sandy mica clay and oolitic siderite sandstone
Gram (Marine)	Rasmussen (1956, p. 16)	Basal layer of glauconitic clay overlain by darkish grey micaceous clay with a slightly brownish tint, overlain by partly bedded, very micaceous clay
Hodde (Marine)	Rasmussen (1961, p. 4 and 32)	Basal gravel layer overlain by a compound bed consisting of sand alternating with layers or lenses of black, micaceous silt and clay. This is overlain by distinctly bedded clay overlain by a black micaceous clay
Odderup (Non-marine)	Rasmussen (1961, p. 4 and 30)	Lignite and quartz sand
Arnum (Marine)	Sorgenfrei (1958a, p. 28)	Alternating layers of greyish brown mica sand, silt and clay with occasional shellbeds in the sandy parts
Ribe (Non-marine)	Sorgenfrei (1958a, p. 28)	Light grey mica sand and gravel
"Klintinghoved" (Marine)	Sorgenfrei (1940, p. 68 and 116)	Black, micaceous clay and whitish, micaceous sand

Table 1. Miocene formations.

The aim of the present paper is to present a detailed review of the application of King's (1983, 1989) North Sea foraminiferal zonation to the Miocene formations of Denmark, facilitating a detailed chronostratigraphic allocation of the zones. Also presented is a refinement of the North Sea zonation, made possible by the dense sampling intervals used (see Figs 1, 13, 14). The northwest European stages are defined by molluscs (*e.g.* Hinsch, 1986); the present study provides an opportunity to compare these with the internationally defined stages.

MATERIALS AND METHODS

Miocene deposits have been examined for their foraminiferal contents in eighteen boreholes in onshore Denmark (Fig. 2). Some of these wells have been analysed in detail, while others have just been scanned for similarities in faunal patterns. Out of eighteen boreholes, eight (see Figs 3, 4, 6-11) have been selected to illustrate the faunal development.

Between 1939 and 1952, several boreholes were drilled by the Danish-American Prospecting Company, some of which have been examined for the present paper, namely Eg-1, Klelund 1+2, and Orre 1+2. The deep oil-exploration wells Arnum-1, Borg-1 (Fig. 4), and Hønning-1 are also included. Other boreholes examined were drilled by the Danish Geological Survey (DGU) between 1951 and 1967, namely Alkærsig (Fig. 6), Burkal, Gram-1 (Fig. 9), Hodde-1 (Fig. 8), Høruphav (Fig. 3), Lille Tønde (Fig. 10), Odderup (Fig. 7), Sæd (Fig. 11), and Tornskov.

In most cases, the only available samples are cuttings, which means that, samples potentially these are subject to downhole contamination (by caving). Accordingly, only the first downhole occurrence in the stratigraphic interpretations is here used. Some of the DGU wells were drilled using the bucket-sample method; samples, each representing approximately 0.5 m, were taken prior to casing of the borehole, and collection of the next bucket sample. In this way, caving can be eliminated.

The 0.5 m sample interval of wells sunken using the bucket-sample method represent dense sampling in comparison to the *c.* 10 m standard interval between samples in North Sea exploration wells. Originally, the NSB (North Sea Benthic) and NSP (North Sea Planktic) zonations of King (1983, 1989) were established on the basis of fossil distribution recorded from North Sea exploration wells. The term 'marker species' is here used for foraminiferal species which define King's (1983, 1989) zones, while the term 'substitute marker' refers to species which in King's range charts are indicated to have their highest occurrence together with the marker species. All species are listed in Table 3, and selected species are illustrated in Pls 1-5.

The relative percentages of selected benthic species are presented in the range charts (Figs 3-4, 6-11). Data from Borg-1 (Fig. 4), Arnum-1 and Hønning-1 have been included to illustrate that some of the new subzones established here may also be used in exploration wells, which, by their nature, have a lower recovery rate.

The 0.1-1.0 mm fraction has been analysed and percentages are shown in the range charts, in view of the fact that original sample sizes were not always available for calculation of concentrations. When fewer than 100 specimens have been counted, the actual number of specimens is given. The planktic foraminiferal content of a sample is indicated as a percentage of the total fauna. Whenever fewer than a total of 100 benthic specimens were counted, the actual number of planktic foraminifera is indicated. Crosses indicate the presence of the most significant planktic species. The actual number of selected species of *Bolboforma* per sample is also indicated.

Palaeoecological interpretations are based on Murray (1971, 1991) and bathymetric zones are defined according to van Hinte (1978), as follows:

- inner neritic: 0-30 m
- middle neritic: 30-100 m
- outer neritic: 100-200 m
- upper bathyal: 200-600 m.

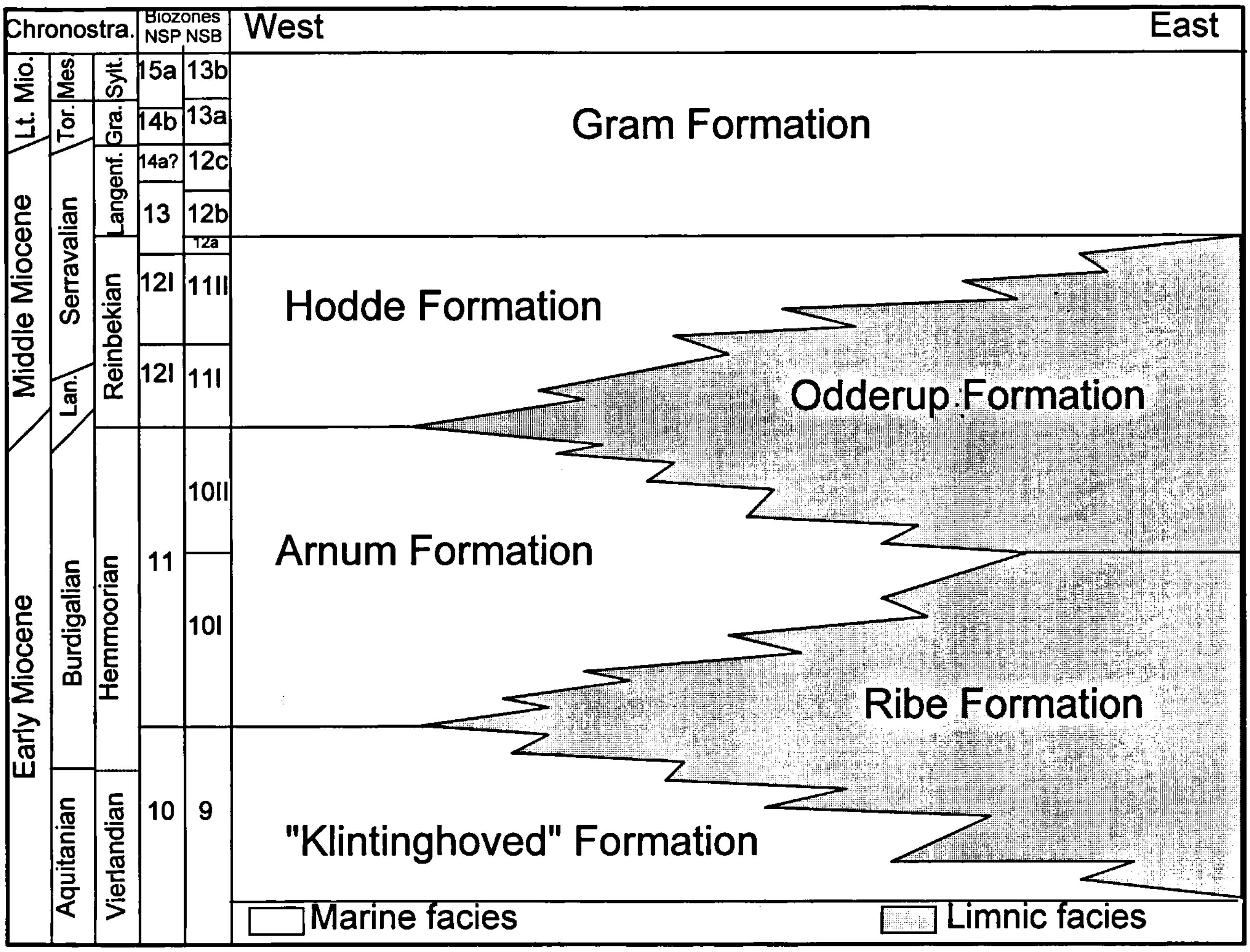

Fig. 1. Schematic overview of the development of the Danish Miocene formations (after Rasmussen, 1961).

DANISH MIOCENE FORMATIONS AND THEIR FORAMINIFERAL CONTENT

1 — 'Klintinghoved Formation' (Early Miocene)

Current knowledge of the oldest Miocene deposits, and of the Late Oligocene/Early Miocene transition is rather poor. Sorgenfrei (1940) described the molluscan fauna of the Klintinghoved Clay, but did not define this as a formation. However, in his 1958b paper, Sorgenfrei did briefly mention the Klintinghoved Formation. This means that the Klintinghoved Formation has never been formally defined; however, the term 'Klintinghoved Formation' is incorporated in overviews of Danish Miocene formations. This unit derives its name from a coastal cliff at Klintinghoved (Als, southern Jylland, see Fig. 2). Strata exposed there, however, are dislocated due to glacial tectonics, and the 'type locality' of the Klintinghoved Formation does not conform to the definition of a formation (Hedberg, 1976).

Sorgenfrei (1940) correlated the molluscan fauna of the Klintinghoved Clay with that of Eger in Hungary, and considered it to be of Aquitanian (Early Miocene) age. However, the Eger molluscan fauna is now considered to be of Late Oligocene/Early Miocene date (Báldi, 1980).

From a borehole at Høruphav (Fig. 2), a few kilometres northeast of Klintinghoved, Sorgenfrei (1961) recorded a molluscan fauna similar to that from the 'type locality'. Foraminifera from another borehole at Høruphav (DGU archives no. 170.381) are discussed in the present study (Fig. 3), and this borehole is here selected as key section to illustrate the 'Klintinghoved Formation' fauna.

Lithology — Sediments at the Klintinghoved outcrop consist of black, micaceous clay and whitish, micaceous sand (Sorgenfrei, 1940, p. 12). In the Høruphav borehole, the 'Klintinghoved Formation' comprises of alternating beds of micaceous dark grey to olive-grey and brownish grey to black fine sand, silt and clay.

The lithostratigraphy of this borehole is as follows (mbs = metres below surface; see also Fig. 3):

79.00-76.80 mbs	light olive-grey marl (Søvind Marl Formation)

76.80-72.40 mbs	glauconitic, dark brown mica-silt and clay (Brejning Clay, part of the Vejle Fjord Formation)
72.40-42.00 mbs	alternating layers of dark grey-dark brown fine mica-sand, -silt and clay.

On fossil content the latter succession is divided into the following formations:

72.40-67.50 mbs	'Klintinghoved Formation'
67.50-59.80 mbs	Ribe Formation?
59.80-58.25 mbs	'Klintinghoved Formation'
58.25-52.80 mbs	Ribe Formation?
52.80-49.45 mbs	'Klintinghoved Formation'
49.45-45.20 mbs	Arnum Formation.

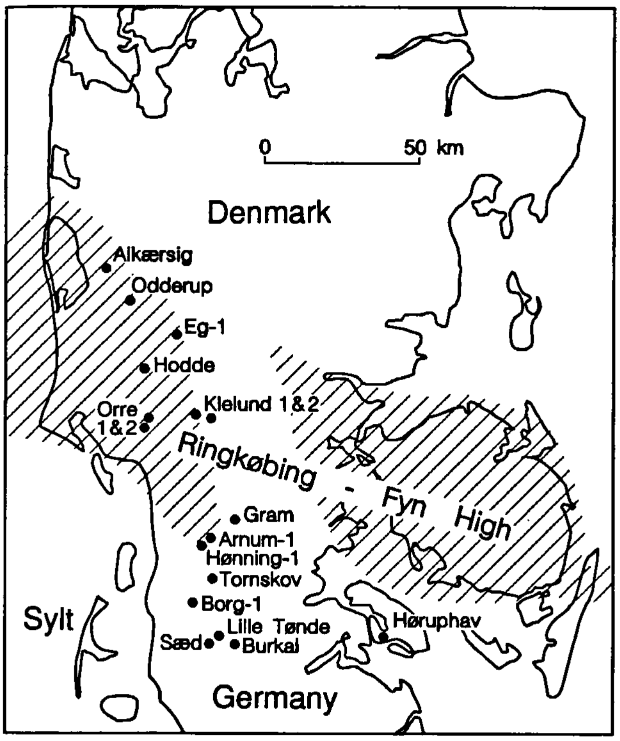

Fig. 2. Map showing the location of the boreholes mentioned in the text; the Ringkøbing-Fyn High, an area of tectonic uplift, is marked by hatching.

Foraminiferal fauna — As the Oligocene/Miocene boundary is represented in the Høruphav borehole, the Late Oligocene NSB 8c Zone is here briefly mentioned. The interval between 72.40 and 76.80 mbs (Brejning Clay, Vejlefjord Formation) in this well (Fig. 3) is assigned to NSB 8c on the highest occurrence of the marker species, *Brizalina antiqua*, and of *Rolfina arnei*.

The 72.40-49.45 mbs interval ('Klintinghoved', and possibly Ribe, formations) is referred to NSB 9 on the highest consistent occurrence of *Plectofrondicularia seminuda* in the 49.45-49.65 mbs sample. This zone may be subdivided into three intervals, as follows:

1 - 72.40-67.50 mbs	
2 - 67.5-53.9 mbs	(the possibly non-marine intervals of the Ribe Formation are included here)
3 - 52.8-49.45 mbs.	

The lowest of these intervals is characterised by *Bolboforma spiralis* (*sensu* Spiegler & von Daniels, 1991; not the NSP 14a indicator of King (1983, 1989), *because B. spiralis sensu* King (1983) is a synonym of *B. subfragoris* (Spiegler & von Daniels, 1991)). The benthic fauna is relatively diverse, comprising *Asterigerina frankei, Bulimina elongata, Valvulineria complanata, Heterolepa dutemplei, H. tenella*, and a few *Nonion boueanum*, whilst planktic foraminifera are absent. The middle interval of zone NSB 9 is rather poor in fossils at Høruphav; only in the middle of this interval does a meagre fauna occur, consisting almost entirely of *Trifarina gracilis* and *T. tenuistriata.*

The index species of NSB 9, *Plectofrondicularia seminuda*, is present only in the uppermost interval of this zone. The associated fauna comprises *A. frankei, B. elongata, Cribrononion heteroporum, Nonion roemeri, T. gracilis, T. tenuistriata, V. complanata, H. dutemplei, H. tenella*, and *Globocassidulina subglobosa*. Planktic foraminifera reappear in this interval. In addition, *Bolboforma rotunda/spinosa* is found in this interval of zone NSB 9; it is here proposed as a substitute marker for the planktic NSP 10 Zone. In borehole Borg-1 (Fig. 4), the highest occurrence of *B. rotunda/spinosa* actually corresponds to that of the marker species of NSP 10, Diatom sp. 4 (see also Fig. 14). *Plectofrondicularia seminuda* has been identified at several localities in Denmark, *viz.* Arnum-1, Hønning-1, the Harre borehole, Sundby, Silstrup, and 'Sorte Knop' at Lodbjerg (Kristoffersen, 1972; Meyer, 1981; Laursen & Kristoffersen, 1995). This suggests that zone NSB 9 may in fact be found throughout most of Jylland.

Environment — The low planktic foraminiferal content, combined with a benthic fauna dominated by the genera *Trifarina, Bulimina* and *Heterolepa*, indicate a restricted marine, middle neritic environment with water depths not exceeding 100 m.

The middle interval has a meagre fauna consisting almost exclusively of *Trifarina gracilis* and *T. tenuistriata*, alternating with barren intervals. This could be due to a high content of organic carbon, indicated also by dark colours, causing a secondary dissolution of the original content of calcareous microfossils. However, the barren intervals could also represent the non-marine Ribe Formation (see Table 1; Fig. 1).

Correlation — The stratigraphic relationship between the NSB 9 fauna and the *'Angulogerina gracilis'* Zone of Ulleberg (1987) is uncertain. However, *P. seminuda* appears to be present in the upper part of that zone; there may be some overlap between these two zones.

In the sequence-stratigraphic framework for the eastern North Sea (Michelsen *et al.*, 1995, 1998), the four sequences 5.2-6.1 occur within zone NSB 9 (Fig. 5). Therefore, we would expect to find these sea level oscillations reflected in the composition of foraminiferal faunas from onshore boreholes. If the barren intervals do indeed represent the non-marine Ribe Formation, they indicate at least two episodes of relative sea level fall, or major lateral movements of the delta front. In the North Sea, the organic carbon content increases upwards through the sequences to reach a maximum in sequence 5.4 (Michelsen *et al.*, 1995, 1998). This might be represented by the *Trifarina* interval at Høruphav.

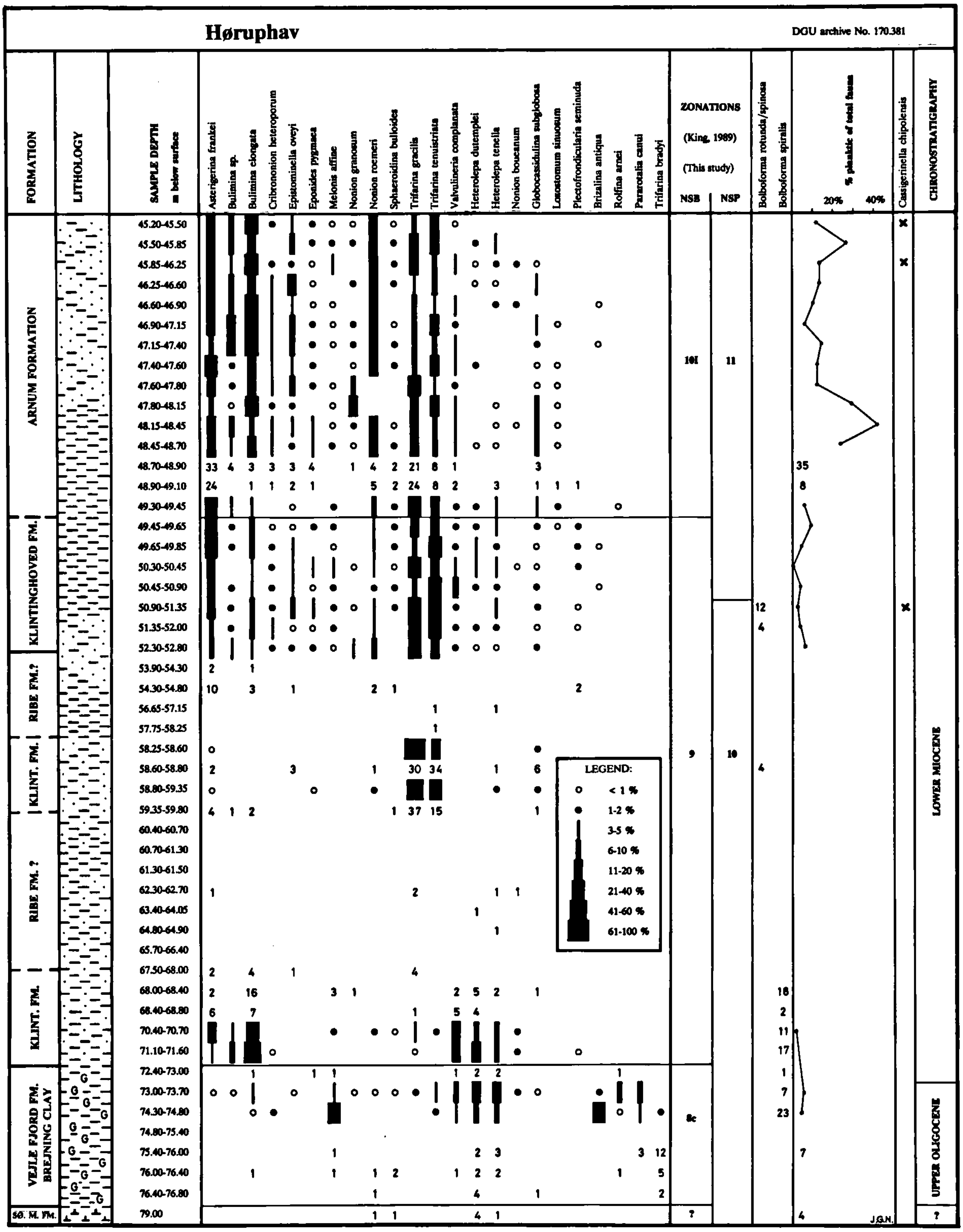

Fig. 3. Range chart of selected microfossils from the Høruphav borehole.

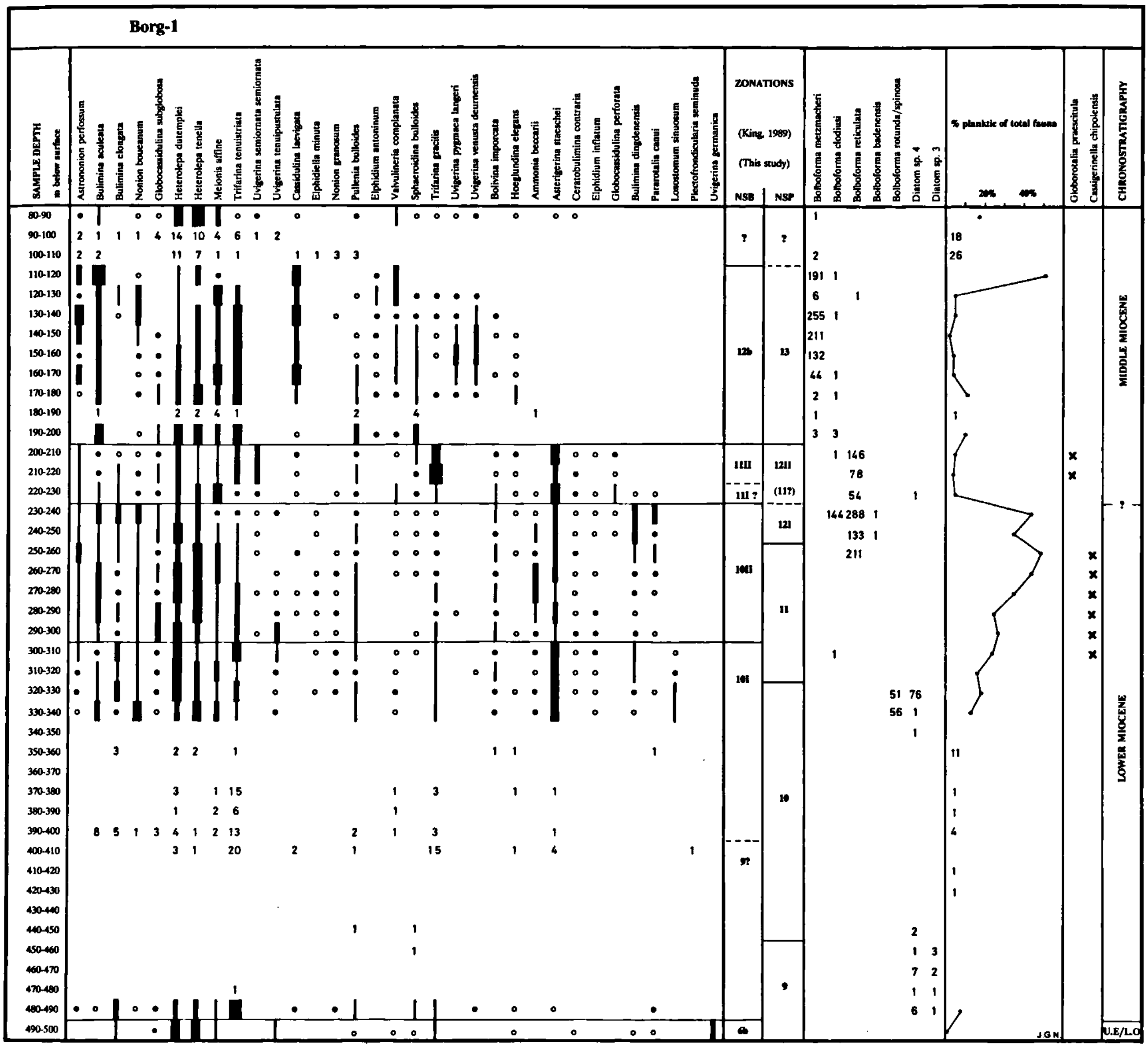

Fig. 4. Range chart of selected microfossils from the exploration well Borg-1 (for legend see Fig. 3).

Borehole	Top Hodde Formation	Top NSB 12a LAD *C. contraria*	Top NSB 11II LAD *A. staeschei*
Alkærsig (Fig. 6)	13.4 m.b.s	-	15.0 m.b.s
Burkal	47.5 m.b.s	48.5 m.b.s	49.5 m.b.s
Gram-1 (Fig. 9)	25.5 m.b.s	25.5 m.b.s	26.5 m.b.s
Gram-2	29.0 m.b.s	-	30.5 m.b.s
Lille Tønde (Fig. 10)	63.6 m.b.s	66.5 m.b.s	66.9 m.b.s

Tab. 2. Location of the top of the Hodde Formation, as based on Rasmussen (1966) compared to the top of NSB 11II (LAD of *Asterigerina staeschei*) and the top of NSB 12a (LAD of *Ceratobulimina contraria*).

Following deposition of sequence 5.4, the organic carbon content decreased in the North Sea and sequence 6.1 might thus correlate with the uppermost interval of NSB 9 at Høruphav, where a relatively rich calcareous fauna is re-established (see Fig. 5).

2 - Arnum Formation (Early Miocene)

The Arnum Formation was defined by Sorgenfrei (1958a, p. 28), on two borehole sections at Arnum (DGU archives nos 150.13, 150.25b); these boreholes have not been analysed for their foraminiferal contents. A borehole at Alkærsig (DGU archives no. 93.101) (Fig. 6; for location see Fig. 2) penetrated a major part of the Arnum Formation, except for the basal part, which has been observed at Høruphav, Fig. 3). In the present study, this borehole is used as key section in the description of the foraminiferal fauna of the Arnum Formation; references to other boreholes will also be made. The quality of the material was sufficient to construct a biostratigraphic subdivision.

The Arnum Formation has previously been regarded to be of the Middle Miocene age (Sorgenfrei, 1958a; Rasmussen, 1966); this matter is discussed further below (see section 'Chronostratigraphic interpretation of biozones').

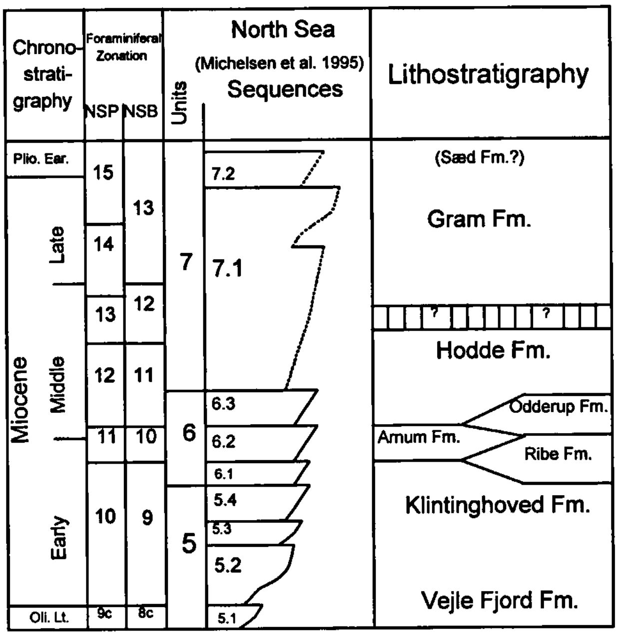

Fig. 5. Stratigraphic scheme comparing the Danish North Sea sequences and the Danish onshore lithostratigraphy (after Michelsen, 1994; Michelsen *et al.*, 1995, 1998).

Lithology — This formation consists of interbedded grey and greyish brown, micaceous sand, silt and clay with occasional shell beds in the sandy intervals (Sorgenfrei, 1958a, pp. 26, 27). The various lithologies presumably explain the varying numbers of foraminifera in our samples (Fig. 6). The lithostratigraphic interpretation of the Alkærsig borehole is as follows (see also Fig. 6):

6.3-10.6 mbs	grey brown mica clay (Gram Clay, Gram Formation)
10.6-13.4 mbs	glauconitic clay (basal part of Gram Formation)
13.4-15.9 mbs	brown to black mica clay (Hodde Clay, Hodde Formation)
15.9-21.0 mbs	grey mica fine sand with occasionally quartz gravel (basal part of the Hodde Formation)
21.0-92.0 mbs	mica silt, alternating with mica clay and quartz sand (Arnum Formation); for more details reference is made to Rasmussen (1961, pp. 17-19).

Foraminiferal fauna — The 91.5-21.0 mbs interval (Fig. 6) is referred to zone NSB 10 on the occurrence of the substitute markers *Bulimina dingdenensis* and *Loxostomum sinuosum*. *Elphidiella minuta* appears to be restricted to the Arnum Formation (NSB 10 Zone) as well (Kristoffersen, 1973). The highest occurrence of *L. sinuosum* may be used to define a new subzone (NSB 10I) in the lower part of NSB 10 as documented in the boreholes Høruphav (Fig. 3), Borg-1 (Fig. 4), Alkærsig (Fig. 6, 91.5-62.2 mbs interval), Odderup (Fig. 7), Arnum-1, Hønning-1, Klelund-1, Burkal, Tornskov, and Orre-2 (see Fig. 12). This subzone is characterised by a fauna dominated *bv Bulimina elongata*, associated with *Heterolepa dutemplei*, *Melonis affine* (sporadic), *Trifarina tenuistriata*, *Astrononion perfossum* (consistently present only in the upper few metres of the subzone together with *B. dingdenensis*), *Nonion boueanum*, *Bulimina sp.*, *Asterigerina staeschei*, *and A. frankei*. The combination of high abundances of *A. frankei* and the presence of *L. sinuosum* in an interval yielding few or no *B. dingdenensis*, is seen in Høruphav (Fig. 2), Alkærsig (Fig. 6), Hodde-1 (Fig. 8), and Klelund-1. Varying amounts of planktic foraminifera also occur in subzone NSB 10I.

The upper part of NSB 10 (61.0-21.0 mbs interval in borehole Alkærsig, Fig. 6), above the *L. sinuosum* Subzone, is named Subzone NSB 10II; it is characterised by a fauna dominated by *B. dingdenensis*, *B. elongata*, and *N. boueanum*. Additional species *are Globocassidulina subglobosa*, *H. dutemplei*, *H. tenella*, *M. affine*, *T. tenuistriata*, *A. perfossum*, *Bolivina imporcata*, *Ammonia beccarii*, and *Pararotalia canui*. In the Alkærsig borehole, *Alliatina* spp. seems to be restricted to the NSB 10II Subzone. Shell beds occur at a few levels in the upper part of the Arnum Formation (NSB 10II); these are characterised by a foraminiferal fauna comprising thick-shelled species such as *A. beccarii*, *N. boueanum* and large miliolids, mainly of the genera *Massilina* and *Quinqueloculina*.

The occurrence of the planktic species, *Globorotalia praescitula* (recognised in boreholes Alkærsig and Odderup, see Figs 6, 7), suggests a correlation with zone NSP 11. *Cassigerinella chipolensis* co-occurs; it is here used as a substitute marker for NSP 11 in the boreholes Høruphav (Fig. 3), Borg-1 (Fig. 4), Alkærsig (Fig. 6), Hønning-1, Eg-1, Burkal, and Tornskov.

Environment — The Arnum Formation faunas show a peculiar feature. The benthic fauna suggests relatively shallow water but the total number of planktic foraminifera is the highest on record to date in the Miocene formations of Denmark. The hydrographic conditions in the palaeo-North Sea basin could thus have enabled fully marine waters to penetrate the neritic realm, transporting planktic species into shallow-water settings. Alternatively, the benthic species could have been washed out into deeper water. The first explanation appears more convincing, taking into account the non-marine deposits of the Ribe and Odderup formations; however, both interpretations would imply strong currents in the palaeo-North Sea.

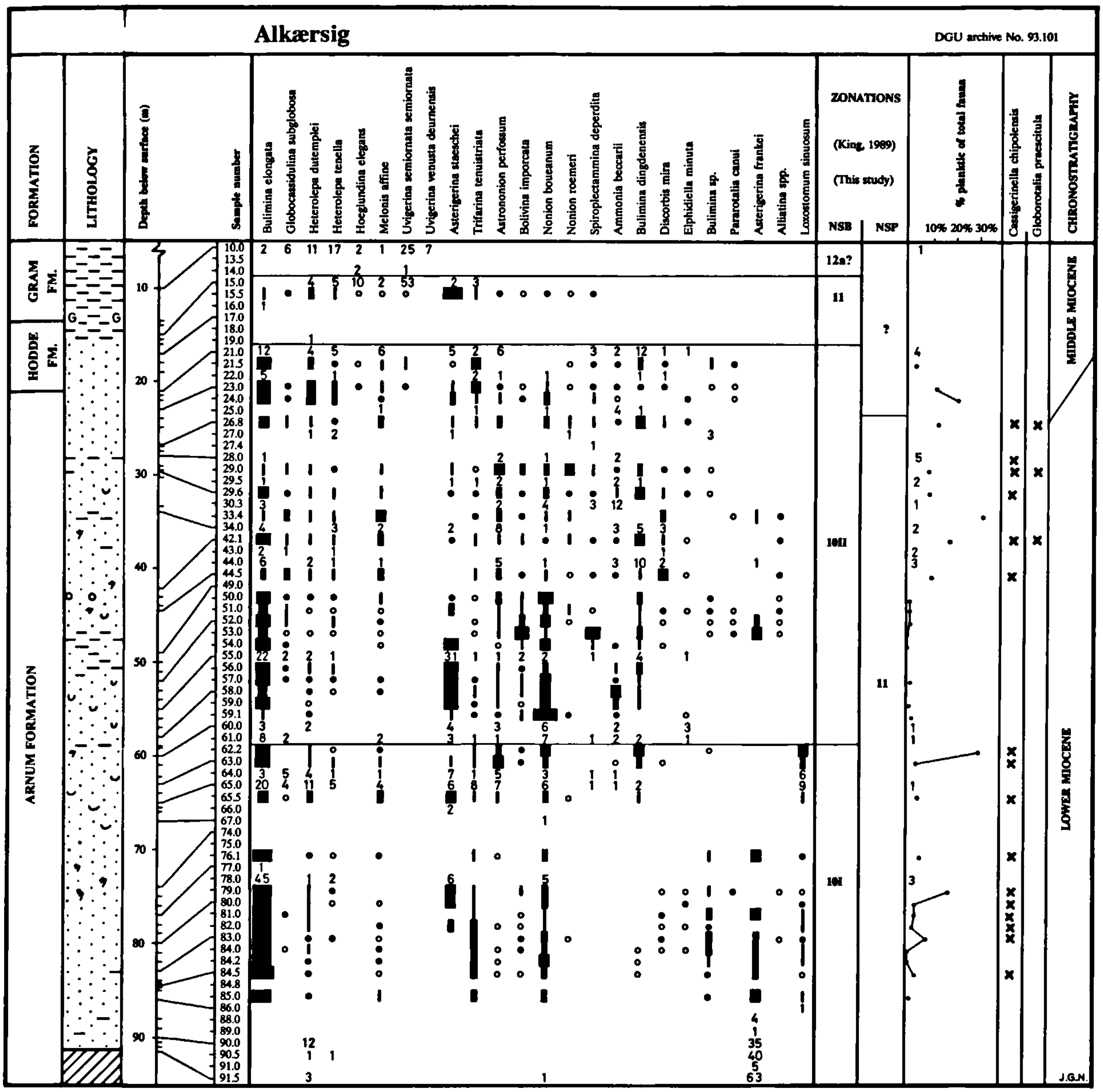

Fig. 6. Range chart of selected microfossils from the Alkærsig borehole (for legend see Fig. 3).

Subzone NSB 10I was probably deposited in deeper water than Subzone NSB 10II. Furthermore, intervals with high numbers of planktic foraminifera (to 42 % at Høruphav, see Fig. 3) have been documented from the middle part of zone NSB 10, and in zone NSP 11, occasionally at the top of subzone NSB 10I (at Høruphav, see Fig. 3; and at Alkærsig, see Fig. 6) and at times in the lower part of subzone NSB 10II (Arnum-1, Hønning-1).

The shell beds and mass occurrence of large miliolids and/or *A. beccarii* in subzone NSB 10II probably represent shallow water in an inner neritic environment. On molluscan evidence, Sorgenfrei (1958a) and Rasmussen (1966) interpreted the water depth of the Arnum Formation to have been between 20 and 50 m. The presence of *A. beccarii* and *P. canui* may reflect reduced salinity in the upper part of the Arnum Formation (subzone NSB 10II), as previously suggested by Sorgenfrei (1958b). The upper Arnum Formation (NSB 10II in the present study) has previously been described as regressive (Friis, 1978). However, the high (to 30%) and rather fluctuating frequency of planktic foraminifera in the Alkærsig borehole (Fig. 6) contradicts this observation.

The depositional environment of the Arnum Formation is rather enigmatic and additional studies are needed to clarify this. The marker species of NSB 10, *Uvigerina tenuipustulata*, has been recognised only in a few onshore boreholes (e.g. Borg-1 (Fig. 4), Orre-2, Arnum-1, and Hønning-1). This may be due to environmental conditions, since *U. tenuipustulata* may have preferred deeper water environments.

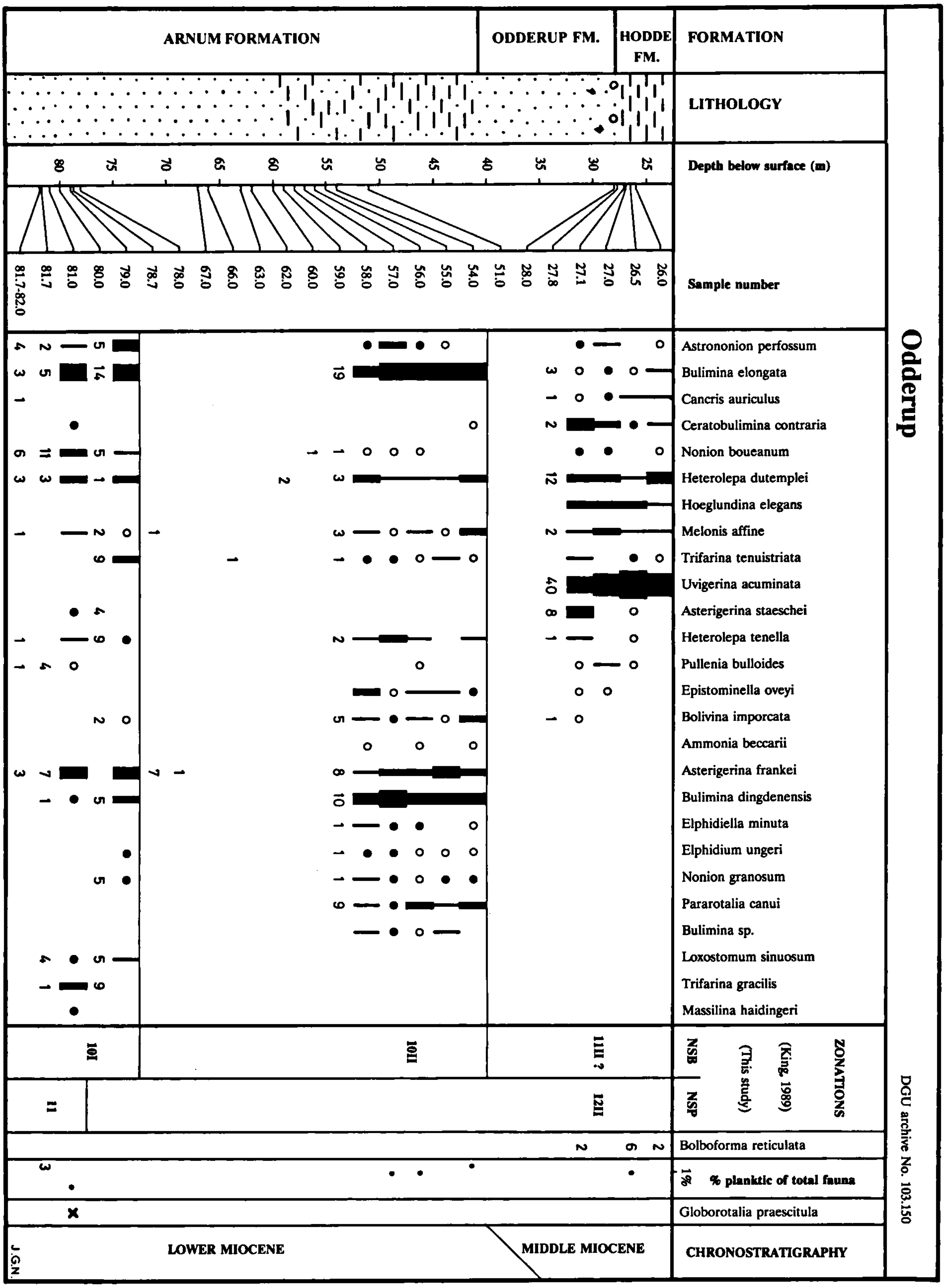

Fig. 7. Range chart of selected microfossils from the Odderup borehole (for legend see Fig. 3).

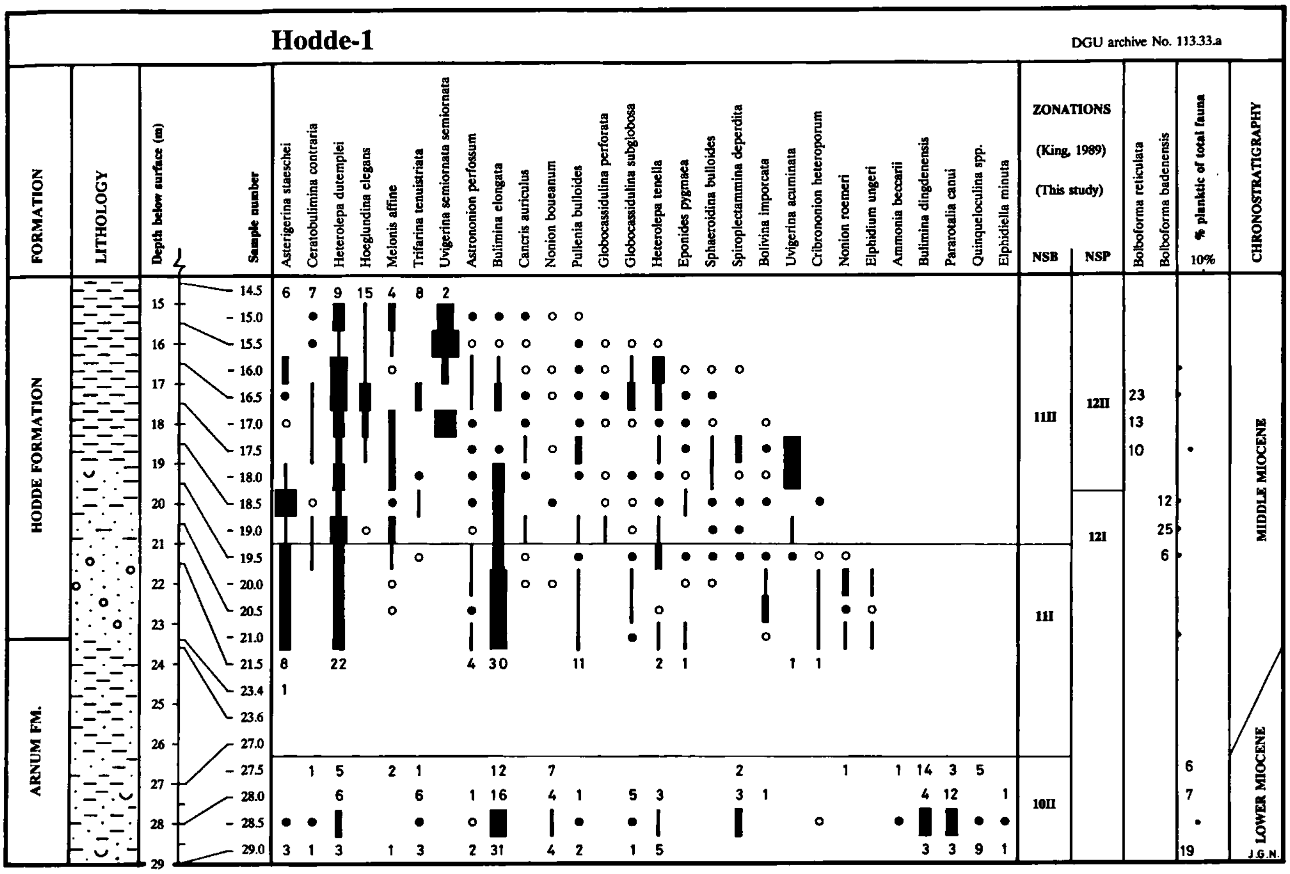

Fig. 8. Range chart of selected microfossils from the Hodde-1 borehole (for legend see Fig. 3).

Correlation — In the eastern North Sea, zone NSB 10 corresponds to sequence 6.2 (Michelsen *et al.*, 1995, 1998); this is in accordance with the fact that, on land, zone NSB 10 (= Arnum Formation) also reflects a water depth increase, followed by a decrease (see Fig. 5).

3 - Hodde Formation (Middle Miocene)

Rasmussen (1961, p. 32) defined the 23.4-13.8 mbs interval in the Hodde-1 borehole (DGU archives no. 113.33.a) as the Hodde Formation. Unfortunately, the highest sample from this borehole (Fig. 8) available for foraminiferal analysis is from 14.5 mbs. In order to cover the entire Hodde Formation, other boreholes, and Gram-1 (DGU archives no. 141.277; 25.50-38.00 mbs interval, see Fig. 9) in particular, have been used as supplement.

Lithology — This formation consists of a basal gravel layer, overlain by a compound bed consisting of greyish sand, alternating with layers or lenses of black, micaceous silt and clay, on top of which rests a distinctly bedded clay followed by a black micaceous clay, named the Hodde Clay (Rasmussen, 1961; Koch, 1989).

The lithostratigraphic interpretation of the Hodde-1 borehole is as follows (see also Fig. 8):

13.8-19.5 mbs	black mica clay (Hodde Clay, upper Hodde Formation)
19.5-21.3 mbs	alternating layers of pale grey mica silt and dark mica clay (lower Hodde Formation)
21.3-23.4 mbs	mica silt with quartz gravel (lowermost Hodde Formation)
23.4-75.2 mbs	alternating layers of mica-sand, silt and clay, occasionally with shell beds (Arnum Formation).

The lithostratigraphic interpretation of the Gram-1 borehole is as follows (see also Fig. 9):

5.30-22.50 mbs	grey-brow mica clay (Gram Clay, upper Gram Formation)
22.50-25.50 mbs	glauconitic mica clay (basal Gram Formation)
25.50-36.50 mbs	black to dark brown mica clay (Hodde Clay)
36.50-38.00 mbs	alternating layers of mica-sand, silt and clay with occasionally quartz gravel (basal Hodde Formation)
38.00-50.30 mbs	alternating layers of mica-silt and clay (Odderup Formation?).

On account of the complex lithology of the lower Hodde Formation, it is often difficult to place its lower boundary accurately. Thus, the lower Hodde Formation may be 'mistaken' for the Odderup or Arnum formations (see also Piasecki, 1980), their lithologies being very similar.

In the Gram-1 borehole occurs a quartz gravel zone in the 37.4-36.5 mbs interval (Rasmussen, 1966); a feature also described from the lowermost Hodde Formation (Rasmussen, 1961, 1966). This would place the alternating layers between 38.0 mbs and TD (Total Depth) in the Gram-1 borehole (Fig. 9) in the Odderup or Arnum formations. Since the interval is rather poor in fossils (caving?) and as none of the characteristic species of the Arnum Formation mentioned above are found in this interval, it is tentatively placed in the non-marine Odderup Formation.

Foraminiferal fauna — The top of zone NSB 11 is defined by the highest occurrence of *Asterigerina staeschei* (see King, 1983); this event seems to occur slightly below the top of the Hodde Formation (see Table 2). On foraminiferal evidence, NSB 11 may be divided into two subzones, NSB 11I and NSB 11II (see Fig. 14). The subdivision may be observed in all boreholes with a well-developed Hodde Formation. In the Odderup and Alkærsig boreholes, the Hodde Formation is not well developed and such a subdivision cannot be made.

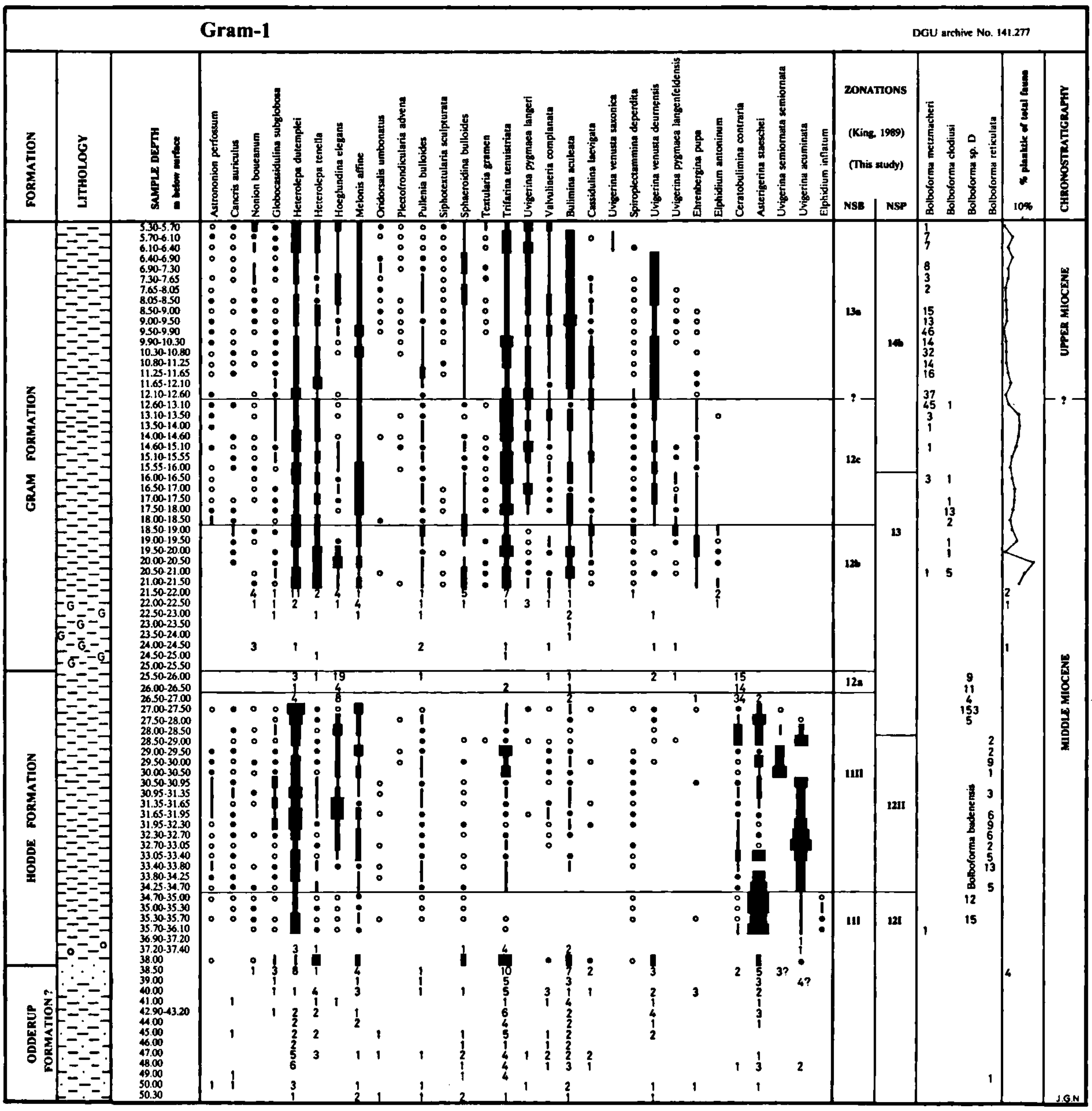

Fig. 9. Range chart of selected microfossils from the Gram-1 borehole (for legend see Fig. 3). The uncertainty regarding NSB 12c indicated by the question mark refers to the use of *E. pupa* as substitute marker; see text for details.

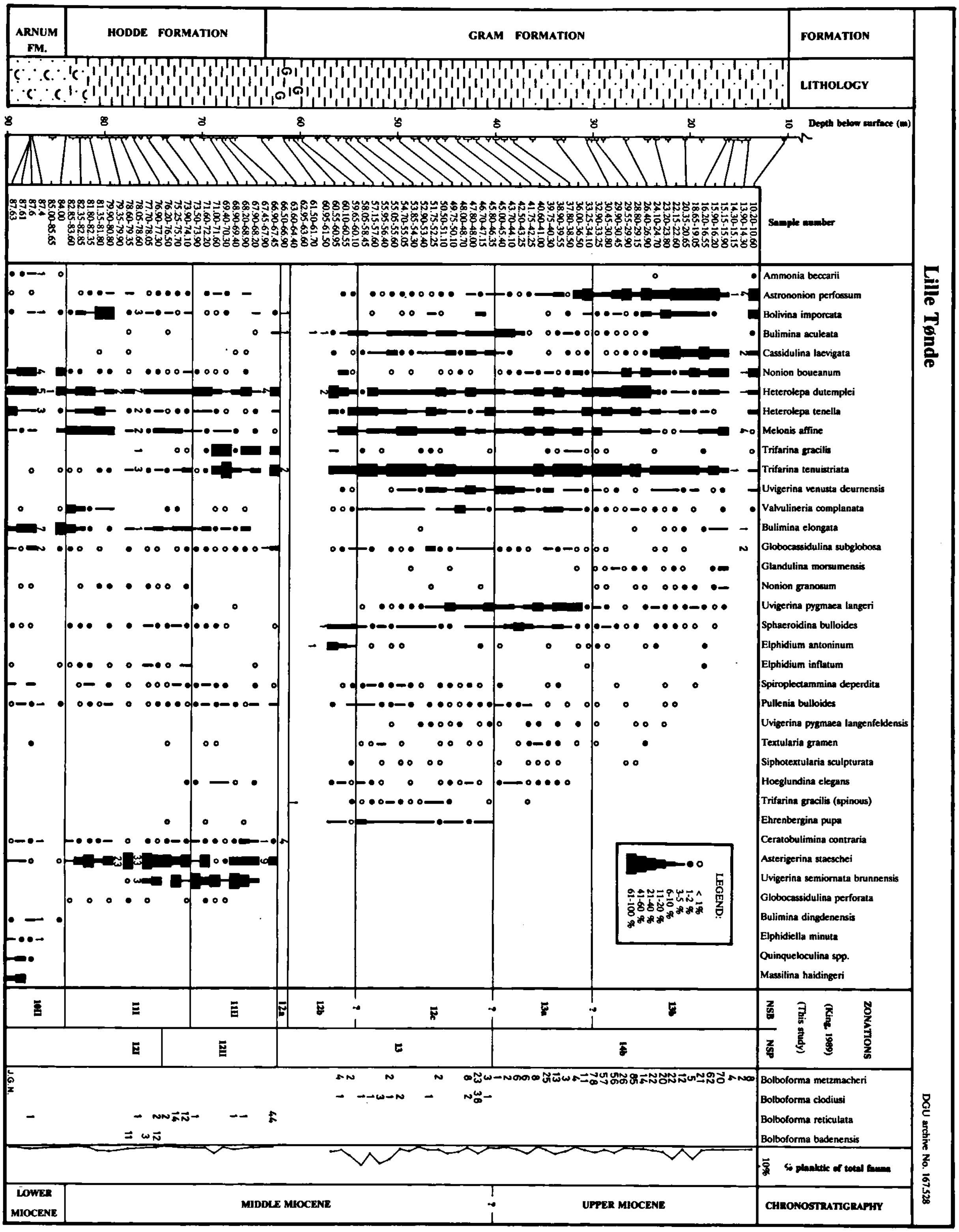

Fig. 10. Range chart of selected microfossils from the Lille Tønde borehole. The uncertainty regarding NSB 12c indicated by the question mark refers to the use of *E. pupa* as substitute marker; see text for details.

Subzone NSB 11I in the lowermost Hodde Formation (i.e. the alternating layers of sand and clay and sometimes the lower part of the Hodde Clay) contains an elphidiid/nonioniid fauna with *Elphidium ungeri, E. inflatum, Cribrononion heteroporum* and *Nonion granosum* (Figs 8-10). In the Gram-1 borehole, *Asterigerina staeschei* has one of its peak occurrences in this lower interval. Additional species are *Heterolepa dutemplei* and *Bolivina imporcata*.

The top of NSB 11II is defined by the highest occurrence of *A. staeschei*; the following species are commoner here than in the underlying subzone: *Hoeglundina elegans*, *Uvigerina acuminata*, *U. semiornata brunnensis*, *U. s. semiornata*, *Globocassidulina subglobosa*, *Ceratobulimina contraria*, and *Bulimina elongata*.

Globocassidulina perforata is restricted to zone NSB 11, as it is in northern Germany (Reinbekian fauna, see Spiegler, 1974). *Ceratobulimina contraria* has its highest occurrence approximately 1 metre above *Asterigerina staeschei* (see Table 2; Figs 9, 10). The accompanying fauna is very sparse, comprising thick-shelled species such as *Hoeglundina elegans* and *Heterolepa dutemplei*. *Uvigerina semiornata saphrophila* is found in this zone at Burkal, which suggests that this zone is correlatable with NSB 12a. As *U. semiornata saphrophila* is found only at Burkal and *Ceratobulimina contraria* has been observed there and at Gram-1 and Lille Tønde, *C. contraria* is here suggested as a substitute marker for NSB 12a.

In the present study, *Bolboforma badenensis* and *B. reticulata* have their highest occurrence within and at the top of NSB 11, respectively. These species are suggested as substitute markers for NSP 12, since the index species, *Sphaeroidinellopsis disjuncta*, has, as yet, not been recorded from Denmark. The occurrence of *Bolboforma badenensis* is usually associated with subzone NSB 11I (Gram-1 and Lille Tønde, Figs 9, 10), or ranges slightly above (Hodde-1, Fig. 8), thus being a marker species of a new planktic subzone referred to as NSP 12I in the present paper. The highest occurrence of *B. reticulata* seems to approximate the top of NSB 11II; this species is here used as marker species for a new subzone, NSP 12II. In the Gram-1 borehole (Fig. 9) an additional reticulate bolboform, *Bolboforma* sp. D, has its highest occurrence at the top of subzone NSB 12a.

Environment — The possibly inner neritic environment of the underlying zone NSB 10 changes into an inner to middle neritic environment in the lowermost portion of NSB 11I, as indicated by *Nonion spp.*, *Elphidium spp.* and *Asterigerina staeschei*, and develops into an outer neritic environment during NSB 11II and NSB 12a, as inferred by the presence of *Hoeglundina elegans*, *Globocassidulina subglobosa*, and *Uvigerina* spp. In Denmark, this is referred to as the Hodde transgression (Friis, 1978, 1989); it corresponds to the Reinbekian transgression in Germany, as based on correlations using *Asterigerina staeschei* (see von Daniels & Gramann, 1988).

Correlation — According to Michelsen *et al.* (1995, 1998) the lower boundary of North Sea sequence 6.3 is within NSB 10. In the present study, the sequence boundary could be placed at the boundary between NSB 10 and 11 (see Fig. 5: at this stratigraphic position a barren interval is observed), or even in the Odderup Formation in the northern part of the study area [Hodde-1 (Fig. 8), Odderup (Fig. 7) and Alkærsig (Fig. 6), see also Fig. 12]. The maximum flooding surface of North Sea sequence 6.3 (Michelsen *et al.*, 1995, 1998) is identified in the middle to upper part of the sequence within NSB 11. The increase in water depth indicated in subzones NSB 11I and 11II probably reflects this.

4 - Gram Formation (Middle/Late Miocene)

The type locality of the Gram Formation is the clay pit of Gram Brickworks (Rasmussen, 1956, p. 16). In the present study, the borehole Gram-1 (Fig. 9) is used as key section for the lower Gram Formation, whilst the Sæd borehole (Fig. 11) covers the upper part.

Lithology — This unit consists of a basal layer of darkish green or black glauconitic clay (Glauconite Clay), followed by darkish grey, micaceous clay with a slightly brownish hue (Gram Clay), on top of which follow occasionally bedded, highly micaceous, silty clay (Rasmussen, 1956, p. 16).

The lithostratigraphic interpretation of the Sæd borehole (Fig. 11) is as follows:

86.40-92.70 mbs	silty, brownish grey mica clay with layers of paler grey mica-silt
92.70-100.10 mbs	brownish grey mica clay

the entire interval studied belongs to the Gram Formation.

Foraminiferal fauna — The Gram Clay is separated from the Hodde Formation by a Glauconite Clay (see above), barren of foraminifera (25.5-22.5 mbs interval in Fig. 9; 63.60-60.95 mbs interval in Fig. 10). The overlying Gram Clay is, however, relatively rich in foraminifera. In the lower Gram Clay, the occurrence of the marker species *Elphidium antoninum* indicates subzone NSB 12b. Slightly above this event, *Bolboforma clodiusi*, index zone NSP 13, has its highest occurrence (Fig. 9). *Hoeglundina elegans* has one of its acmes here in subzone NSB 12b. In the accompanying fauna *Heterolepa dutemplei*, *Sphaeroidina bulloides*, *Trifarina tenuistriata*, and *Bulimina aculeata* dominate. *Uvigerina pygmaea langeri* is present but rare.

None of the index species of subzone NSB 12c (*Uvigerina* sp. A) and the correlative subzone NSP 14a (*Bolboforma subfragoris* = *B. spiralis sensu* King, 1983, 1989) are known from the boreholes studied, but the highest occurrence of *Uvigerina pygmaea langenfeldensis* could indicate the possible presence of NSB 12c. In King's (1989, p. 439) range chart, *U. p. langenfeldensis* ranges from the middle of NSB 12c to the lower part of subzone NSB 13a. In the present study, this taxon is tentatively used as an indicator of NSB 12c. This subzone is not well developed in onshore Denmark, probably as a result of unsuitable environmental conditions.

In the North Sea, the highest occurrence of *Ehrenbergina pupa* is at the top of subzone NSB 12c (Laursen *et* *al.*, 1992); this event can probably be used as a substitute marker for the top of NSB 12c. In addition to *Uvigerina pygmaea langenfeldensis* and *E. pupa*, the fauna of the presumed subzone NSB 12c includes *Bulimina aculeata, Cassidulina laevigata, Heterolepa dutemplei, H. tenella, Melonis affine*, and *Trifarina tenuistriata*. It should also be noted that *Hoeglundina elegans, Uvigerina pygmaea langeri* and *U. venusta deurnensis* are relatively common in this interval. A spinous form of *Trifarina gracilis* has been observed in this interval in the Lille Tønde borehole (Fig. 10).

Bolboforma metzmacheri and *Uvigerina pygmaea langeri* range from the highest sample of borehole Gram-1 (Fig. 9) down to the lower part of the presumed subzone NSB 12c. These are the index species of subzones NSP 14b and NSB 13a, respectively, and indicate that at least part of NSB 13a is represented. NSB 13a is also found in the Lille Tønde borehole (Fig. 10). The fauna of NSB 13a is dominated by *Trifarina tenuistriata, Melonis affine* and *Heterolepa dutemplei. Hoeglundina elegans* and *Sphaeroidina bulloides* reach their acmes in this subzone.

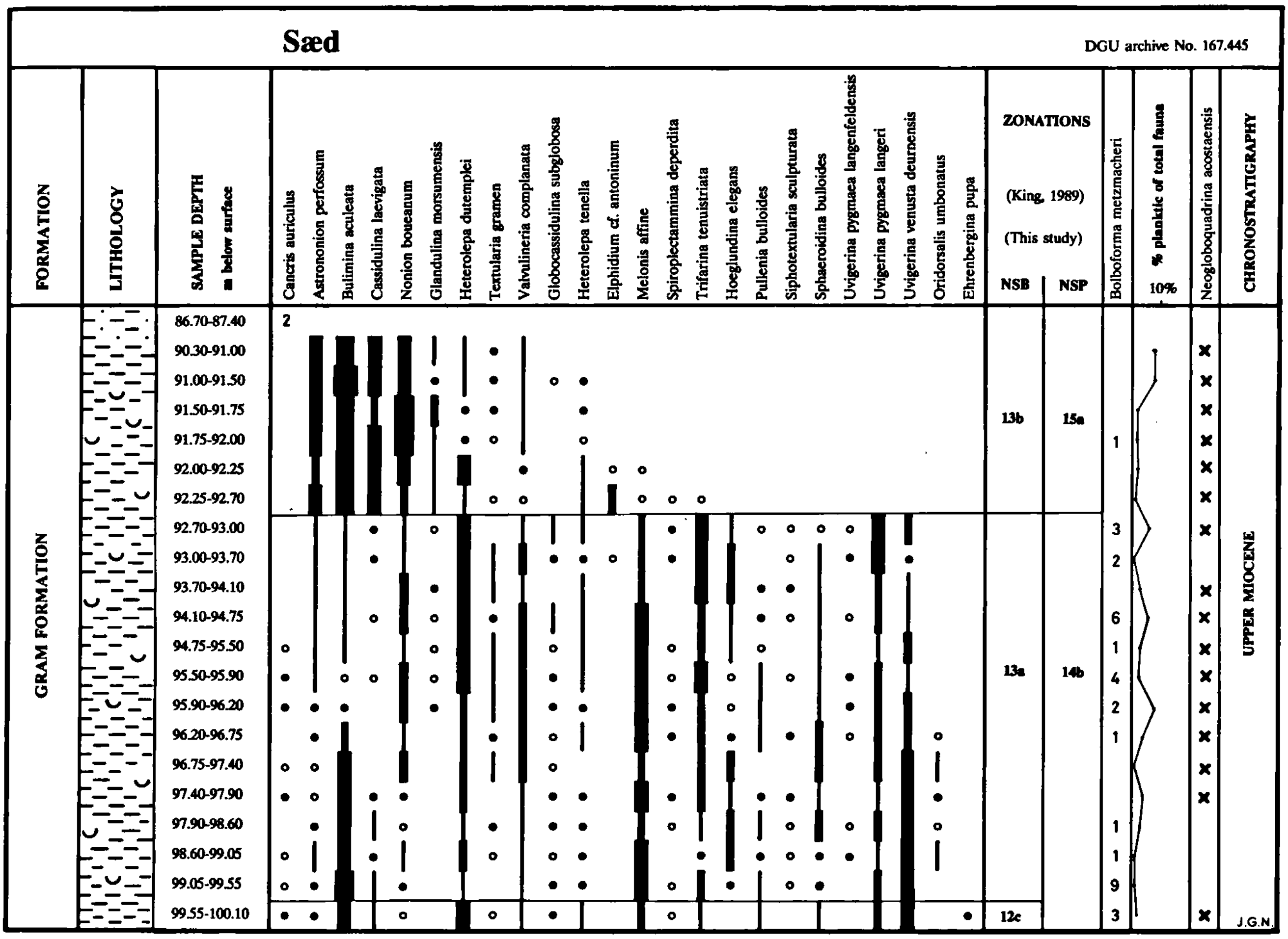

Fig. 11. Range chart of selected microfossils from the Sæd borehole (for legend see Fig. 3).

In the Sæd borehole (Fig. 11), the boundary between NSB 13a and NSB 13b at 92.7 mbs corresponds to the highest occurrences of several species, to an abrupt faunal change, as well as to a slight change in lithology (Rasmussen, 1966, p. 320) indicating a possible hiatus. *Bolboforma metzmacheri* and *Uvigerina pygmaea langeri* are found in the 'typical' Gram Clay below 92.7 m in this borehole. These species indicate the presence of NSB 13a and NSP 14b.

No index species of NSB 13b are present in the interval above 92.7 mbs, but a substitute marker of NSB 13b (King, 1989, p. 439), *Valvulineria complanata* (= *V. mexicana grammensis* of King, 1983, 1989), is found. The low diversity fauna is dominated by *Astrononion perfossum, Bulimina aculeata, Cassidulina laevigata*, and *Nonion boueanum. Glandulina morsumensis* is virtually restricted to this subzone. The planktic *Neogloboquadrina acostaensis*, index species of NSP 15a, also occurs in this interval.

A similar interval seems to be present at Lille Tønde (Fig. 10). In subzone NSB 13b *Astrononion perfossum* increases in abundance, as do *Nonion boueanum, Cassidulina laevigata*, and *Trifarina tenuistriata*, in an interval yielding *Glandulina morsumensis. Bulimina aculeata* occurs in the Sæd borehole but is unknown from the Lille Tønde borehole in this interval. With *Trifarina tenuistriata* it is the other way around; this species does occur in the Lille Tønde borehole, but is absent from this interval at Sæd (compare Figs 10, 11).

A variety of *Elphidium antoninum* occurs close to the boundary between NSB 13a and NSB 13b.

In the Lille Tønde borehole, *Bolboforma metzmacheri* and *Uvigerina pygmaea langeri* occur in an interval assigned to NSB 13b, based on the occurrence of *Uvigerina venusta deurnensis*. The presence of *Bolboforma metzmacheri* and *Uvigerina pygmaea langeri* in this interval could be the result of reworking, since these taxa are fairly common in the uppermost NSB 13a. However, it cannot be excluded that *B. metzmacheri* does actually occur in situ in most of subzone NSB 13b.

Environment — In NSB 12, *Hoeglundina elegans, Bulimina aculeata, Trifarina tenuistriata, Sphaeroidina bulloides*, a few species of Uvigerina, the non-keeled *Elphidium antoninum*, as well as approximately 10% planktic foraminifera in subzone NSB 12b, suggest a middle to outer neritic environment.

In subzone NSB 12c, *H. elegans, S. bulloides* and *Pullenia bulloides* and the high numbers of species of *Uvigerina* and planktic foraminifera indicate an outer neritic environment, with even greater water depths than in the preceding subzones. This observation is corroborated by the presence of *Bulimina aculeata, Cassidulina laevigata, Melonis affine, Trifarina tenuistriata* and *Globocassidulina subglobosa.*

Water depth in subzone NSB 13a appears to have increased further when compared to the underlying subzones. The dominant species here are those of subzone NSB 12c, but their higher abundance could imply increased water depths.

The lower numbers of planktic foraminifera in NSB 13b, together with a decrease of *P. bulloides* and *S. bulloides*, the absence of *Hoeglundina elegans*, as well as increased numbers of *Astrononion perfossum, Bulimina aculeata*, and *Nonion boueanum* in comparison to the underlying subzone NSB 13a, is here seen as evidence of a decreasing water depth and a change to middle neritic conditions. The continuous presence of planktic foraminifera, however, suggest that fully marine conditions still prevailed.

The above interpretations of the environments match Spjeldnæs's (1975) views that the Gram Formation was deposited on an open shelf in marine waters of normal salinity and a water depth of approximately 100 m.

Correlation — The Glauconite Clay at the base of the Gram Formation is either barren of, or yields only sparse foraminiferal faunas. Similar unfossiliferous units were described by Indans (1962), Ellerman (1963), Spiegler (1974), and Laursen (1992) for northern Germany. The three last-named authors found a barren or impoverished zone between deposits of Reinbekian and Langenfeldian age. Molluscs from the Sæd and Lille Tønde boreholes (Poulsen *et al.*, 1995) indicate a Syltian age for the interval with *Glandulina morsumensis* (NSB 13b).

The base of the North Sea sequence 7.1 of Michelsen *et al.* (1995, 1998) is placed in NSB 11 (Fig. 5) and the maximum flooding surface at the top of NSB 12. According to onshore data, the maximum water depths occurred in NSB 13a. These observations do not conflict, since the relative sea level may continue to rise after the deposition of the maximum flooding surface (Loutit *et al.*, 1988).

5 - 'Sæd Formation'

The Sæd Formation was first mentioned by Sorgenfrei (1958b), but has never been formally defined. Rasmussen (1958) described the molluscan fauna from a borehole at Sæd, and introduced the term 'Sæd Clay'. Subsequently, Rasmussen (1961, p. 39) stated that the 'Sæd Clay' should be included in the 'Sæd Formation', together with some siderite sandstone. However, based on molluscan faunas from the 93.30-92.70 mbs interval in another borehole at Sæd (i.e. that presented here), Rasmussen (1966, p. 320) concluded that this clay should be assigned to the Late Miocene Gram Clay, and constituted a distinct assemblage zone. He further concluded (p. 324) that the Sæd Clay fauna (*sensu* Rasmussen, 1958) belonged to this assemblage zone. Thus, the Sæd Formation ceased to exist.

Bertelsen & Kristoffersen (1974) compared the upper part of the Sæd borehole section (86.4 to 72.0 mbs interval), with a borehole on Rømø and Morsum Cliff (Sylt), and placed this at the Late Miocene/Early Pliocene transition.

DISCUSSION

The biostratigraphical results of the present study are summarised in Fig. 12. The most complete succession of biozones is found in southern Jylland; to the north, the succession is interrupted by unfossiliferous intervals, either as a result of the delta progradations of the non-marine Ribe and Odderup formations or of secondary dissolution of foraminiferal faunas. Danish onshore deposits represent a shallower water environment than coeval deposits in the central North Sea. Environmental variations are reflected more clearly in shallow-water faunal assemblages, and are thus more easily recognised in onshore deposits.

NSB 9

This zone is well represented at Høruphav (Figs 3, 12), is also found at Arnum-1, Hønning-1, and may be present in Borg-1 (Fig. 4). The palaeowater depth seems to have slightly increased towards the south, as indicated by higher numbers of *Trifarina tenuistriata* and planktic foraminifera there.

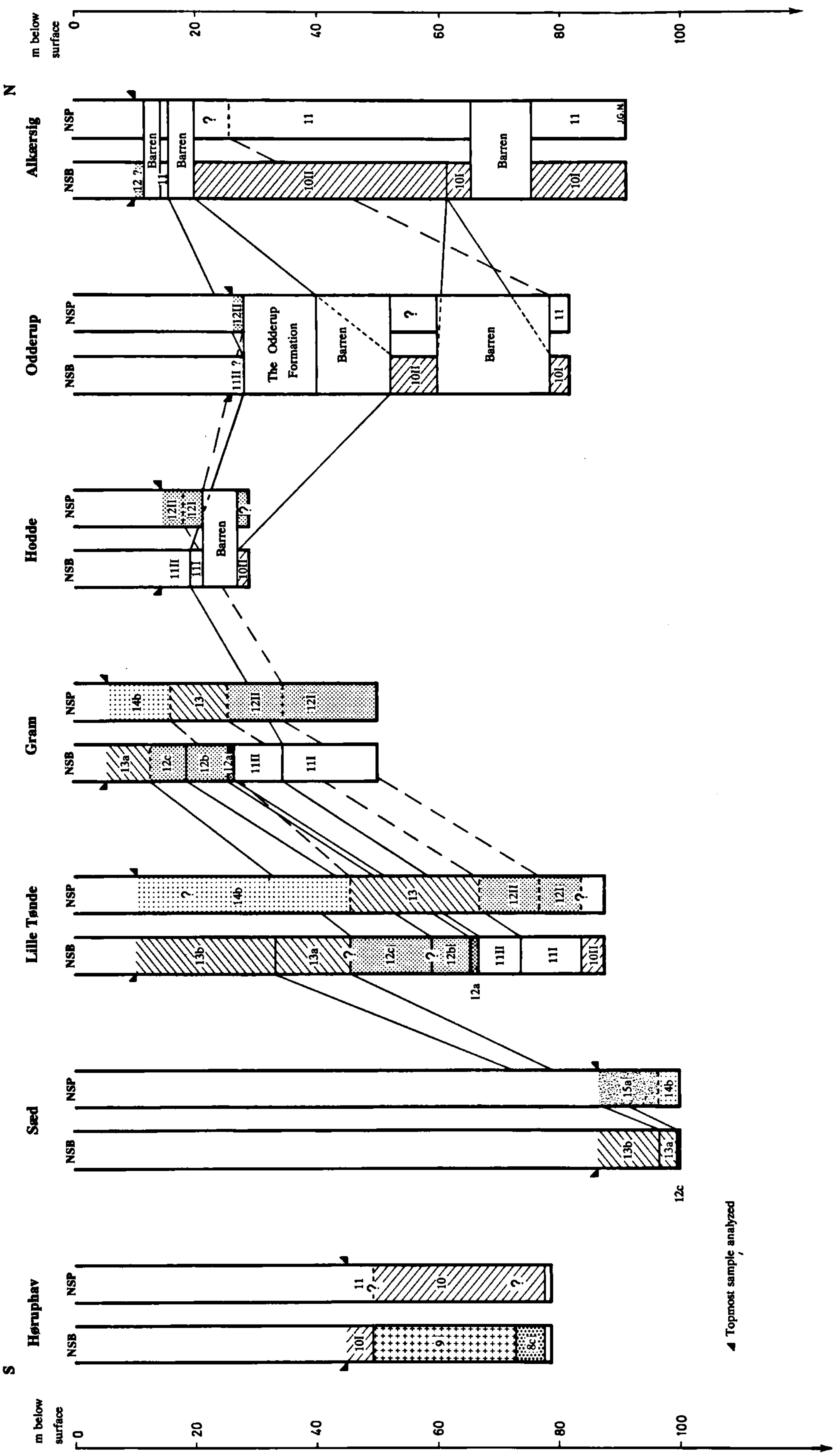

Fig. 12. South-north profile of the analysed boreholes; correlations between the zones/subzones of the boreholes are indicated.

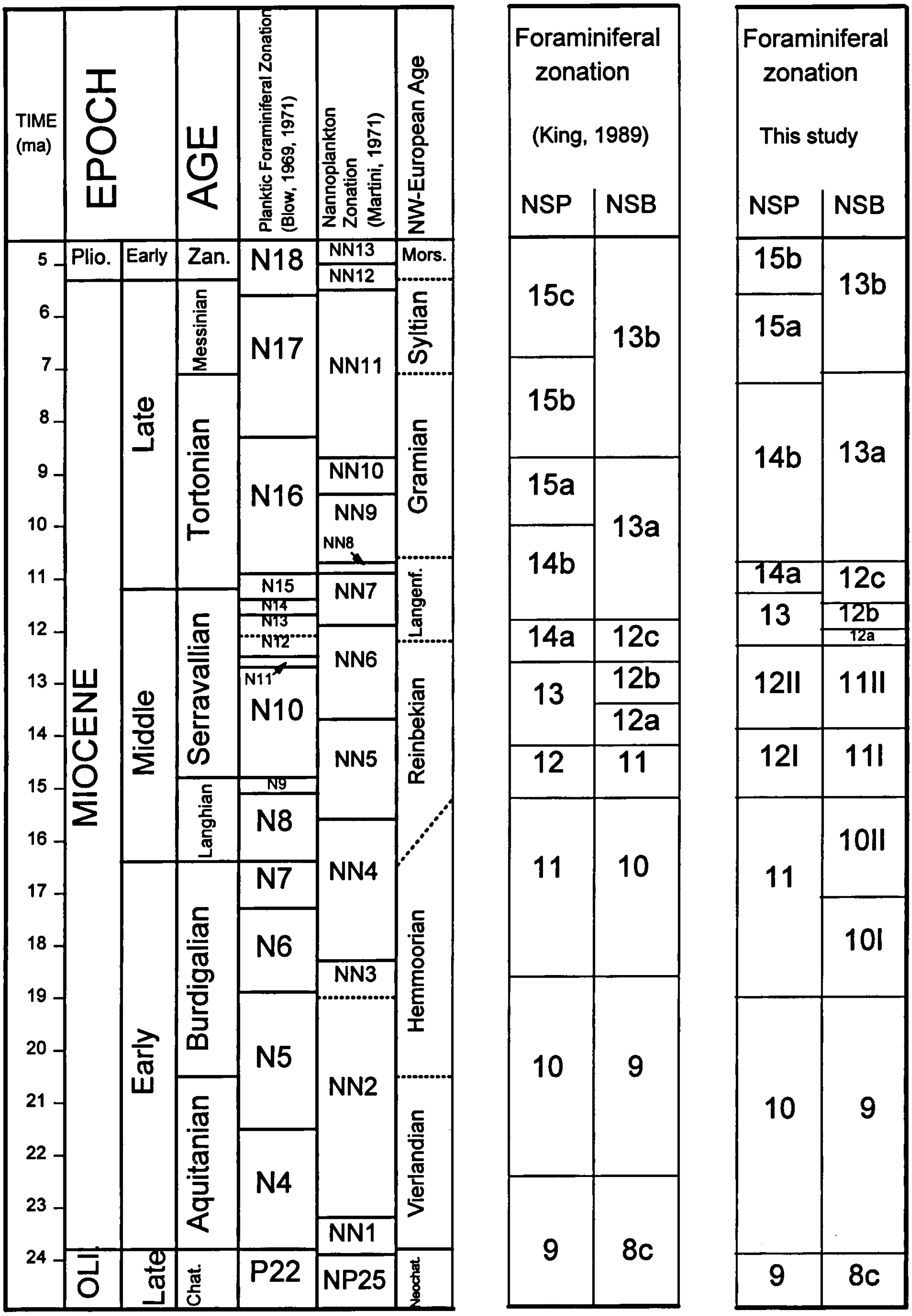

Fig. 13. Correlation of the NSP and NSB zones to the international plankton zones. Calibration between the nannoplankton and the planktic foraminiferal zonation is based on Berggren *et al.* (1995).

BIOSTRATIGRAPHIC EVENTS

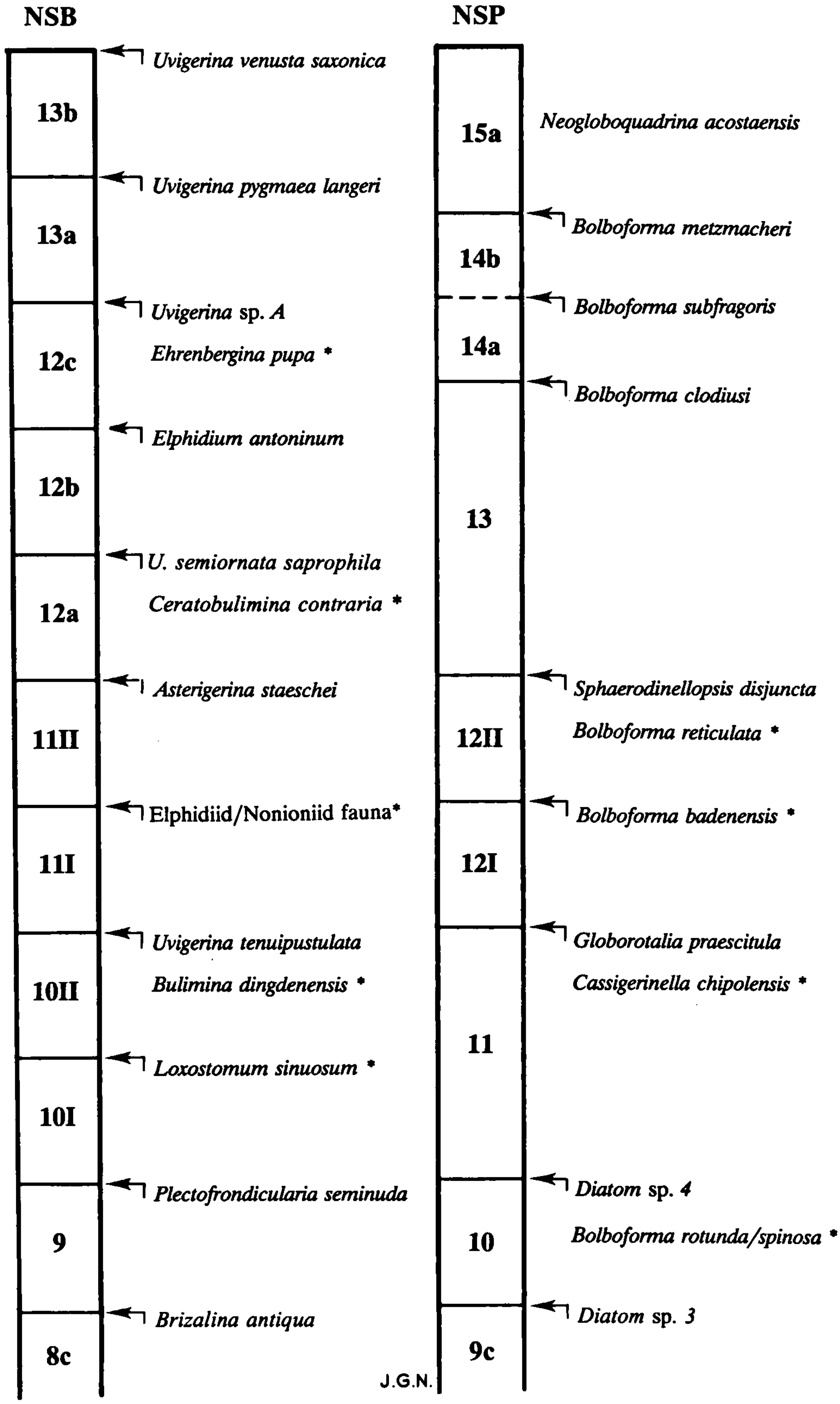

Fig. 14. Biostratigraphic events indicating the upper zonal boundaries. Species marked by an asterisk are either those suggested here as substitute markers or those introduced as index fossils in the present study.

Bolboforma rotunda/spinosa, introduced in the present paper as a substitute marker of NSP 10, has its highest occurrence 1 m below the top of NSB 9 in the Høruphav borehole (Fig. 3), and in Borg-1 co-occurs with Diatom sp. 4, the marker of NSP 10 (Fig. 4). Hitherto, the upper limits of NSB 9 and NSP 10 were considered to be coeval (King, 1989); however, in a commercial oil well where sampling intervals commonly comprise 10 m, zonal boundaries would probably be registered as concurrent.

NSB 10

The lowermost part of NSB 10I is seen at Høruphav (Figs 3, 12), while the most extensive succession has been observed in Borg-1 (Fig. 4). There seems to be an unfossiliferous interval at the top of NSB 10I, north on the Ringkøbing-Fyn High (Odderup, Fig. 7, and in part, Alkærsig, Fig. 3), but not south of this area (Arnum-1, Hønning-1 and Borg-1, Fig. 4) (see Figs 2, 12). Based on current data, it cannot be determined whether this lack of fossils should be ascribed to dissolution or to a non-marine environment. A second barren interval is observed at the top of NSB 10II in Hodde-1, Odderup and Alkærsig, but not in Borg-1, Hønning-1 and Arnum-1. At Odderup, part of this unfossiliferous interval has been defined as the Odderup Formation. However, it cannot be conclusively determined whether the barren intervals in Hodde-1 and Alkærsig should also be placed in the Odderup Formation or should be interpreted as the result of dissolution.

When environmental conditions of NSB 10I as a whole are considered, the faunas of the Odderup and Eg-1 boreholes (Fig. 2) seem to indicate shallowest water conditions, which corresponds well with their location on the Ringkøbing-Fyn High.

The maximum thickness of NSB 10II is observed in the Alkærsig and Arnum-1 boreholes. The environmental setting was roughly similar to that of NSB 10I, *i.e.* the Odderup borehole appears to represent the shallowest water setting.

The top of NSP 11 is held to be coeval with the top of NSB 10 (King, 1983, 1989) in the central North Sea. Onshore, however, the top of NSP 11 appears to be below the top of NSB 10 in all the boreholes studied in the present paper (Figs 4, 12). This is probably an effect of the shallow water depth limiting the distribution of planktic foraminifera.

NSB 11

Subzone NSB 11I is found at Hodde-1 (Fig. 8), and in other boreholes south of this (Figs 2, 12). In Borg-1 and Lille Tønde (Figs 4, 10), this subzone is not as well developed as in the other boreholes. The occurrence of *Bolboforma badenensis*, a marker for subzone NSP 12I, appears related to NSB 11I or the lowermost part of NSB 11II (at Hodde-1). In Borg-1, however, only a single specimen of *B. badenensis* has been observed in the two highest samples in subzone NSB 10II.

NSB 11II, the top of which is marked by the highest occurrence of *Asterigerina staeschei*, is found in most of the boreholes studied. The greatest thickness is found in the south; the subzone thins to the north over the Ringkøbing-Fyn High.

The top of NSP 12II, as indicated by the suggested substitute marker *Bolboforma reticulata*, is apparently coeval with the top of NSB 11II (Figs 12, 13).

NSB 12

King (1983) defined the top of NSB 12a as the highest occurrence of *Uvigerina semiornata (s. lat.)*. King (1989) renamed this subzone as *Uvigerina semiornata saprophila* Subzone, following taxonomic revision. The definition of the subzone thus became more restricted, making it less readily recognised in subsequent studies. NSB 12a (*sensu* King, 1983) is found in the Alkærsig borehole (Fig. 6) in the lowermost part of the Gram Formation, while NSB 12a (*sensu* King, 1989) is found in the topmost part of the Hodde Formation in boreholes mentioned in Table 2 as inferred from correlation with Burkal, the only borehole from which *Uvigerina semiornata saprophila* has been recorded so far. As this taxon has been found only at Burkal and *Ceratobulimina contraria* has been observed there, as well as in Gram-1 and Lille Tønde, *C. contraria* is suggested as a substitute marker for NSB 12a.

These observations indicate that NSB 12a correlates with the normally barren glauconite clay found at the base of the Gram Clay (see also Laursen & Kristoffersen, 1995), and the topmost part of the Hodde Formation.

The top of NSB 12b, defined by the highest occurrence of *Elphidium antoninum*, is found in the Gram-1 and the Lille Tønde boreholes. The zonal boundary is best defined in the Gram-1 borehole (Fig. 9). The diffuse highest occurrence of *Elphidium antoninum* in the Lille Tønde borehole (Fig. 10) could be the result of reworking. The palaeowater depth for this subzone appears to have been deeper at Gram-1 than at Lille Tønde, as indicated by higher numbers of *Hoeglundina elegans* and planktic foraminifera at the former.

The top of NSP 13 equates with the top of NSB 12b according to King (1983, 1989). However, in the two boreholes where NSP 13 is recorded in the present paper, the top of the zone occurs within or at the top of NSB 12c (Figs 9, 10, 12). These data suggest that the top of NSP 13 should be adjusted to a level within NSB 12c (see Figs 1, 13, 14).

Subzone NSB 12c itself is poorly defined in the boreholes as none of the index species are present. However, in the present study the highest occurrence of *Ehrenbergina pupa* is suggested as a possible substitute marker of NSB 12c. Like NSB 12b, palaeowater depth seems to have been deeper at Gram-1 than at Lille Tønde, as indicated by a higher number of species of *Uvigerina* at the former.

Subzone NSP 14a, indicated by the highest occurrence of *Bolboforma subfragoris* (= *B. spiralis sensu*

King, 1983, following taxonomic revision by Spiegler & von Daniels, 1991) has not been observed in onshore Denmark.

NSB 13

NSB 13a has been documented at Sæd, Lille Tønde and Gram-1 (Figs 9-12). Palaeowater depth seems to have been the same for most of this part of the basin.

NSB 13b is present in the Sæd and Lille Tønde boreholes; sediments at the latter locality are probably reworked as the faunal picture there is less clear than at Sæd. These boreholes are approximately 5 kilometres apart, but palaeowater depth at Lille Tønde seems to have been deeper than at Sæd, as based on presence of *Trifarina tenuistriata* at the former.

The top of subzone NSP 14b, as indicated by the highest occurrence of *Bolboforma metzmacheri*, is assumed to occur within the upper part of NSB 13a (King, 1983, 1989). The results from Sæd, Lille Tønde and Gram-1 are ambiguous, as the highest occurrence of *B. metzmacheri* has been documented at the top of NSB 13a, probably just below a hiatus at Sæd (Fig. 11). The highest frequency of *B. metzmacheri* occur in subzone NSB 13b at Lille Tønde (Fig. 10). In Gram-1, the highest occurrence of *B. metzmacheri* is in the topmost sample (Fig. 9), still in NSB 13a. Of these, the Lille Tønde borehole should be expected to document the highest stratigraphical occurrence of *B. metzmacheri*. However, Lille Tønde is here interpreted as showing some reworking. The higher frequency of *B. metzmacheri* in the NSB 13b interval, in comparison to subzone NSB 13a at Lille Tønde, could be explained by the fact that *Bolboforma* is more resistant than foraminifera (Spiegler, pers. comm., 1993) and thus less likely to be destroyed during reworking. With no conclusion drawn from the present data, the top of subzone NSP 14b is placed within the uppermost part of NSB 13a, as suggested previously by King (1983, 1989) (see Fig. 13).

CHRONOSTRATIC INTERPRETATION OF BIOZONES

The most widely used standard Cenozoic biostratigraphic zonations are based on planktic foraminifera (N and P zones, as defined by Blow, 1969, 1979) and on calcareous nannoplankton (NN and NP zones, as defined by Martini, 1971). At North Sea latitudes, however, some of the key nannoplankton and foraminiferal species are absent, and planktic foraminifera occur only irregularly in the North Sea basin. In part, this may be due to the North Sea's tenuous connection with open ocean waters, and/or to post-depositional destruction of the more fragile planktic species.

To date, King's (1983, 1989) zonation is the most comprehensive of its kind in the North Sea area; the zones are fairly easily recognised. Therefore, we have decided to use and develop this zonation in the present paper, and to some extent, adopt the chronostratigraphic interpretation of these zones. Some modifications of King's (1983, 1989) chronostratigraphic conclusions are discussed below.

In Fig. 13, a tentative correlation between the North Sea zonation and the international plankton zones is illustrated. The correlation between nannoplankton (NN) and planktic foraminiferal (N) zones is that proposed by Berggren *et al.* (1995); the calibration between the NW European stages and the international stages is adopted from Laursen *et al.* (1998).

NSB 8c

The base of the Miocene is represented in the Høruphav borehole (Fig. 3), where NSB 8c (Late Oligocene) is found; the top of NSB 8c corresponds roughly to the top of NSP 9 (King, 1983, 1989). Gradstein *et al.* (1992) recorded *Almaena osnabrugensis*, a substitute marker of NSB 8c, in an interval assigned to P 22.

In the Høruphav borehole, *Rolfina arnei* co-occurs with the marker species *Brizalina antiqua*. The former taxon has an acme in NP 25, but its full range extends from NP 24 to NN2 (Laursen, 1994).

According to King (1989, p. 447), the top of NSB 8c cannot be accurately placed, but may be within the NP 25-NN 2 interval. Taking Gradstein *et al.*'s (1992) observation into consideration, the boundary is tentatively placed in the uppermost Oligocene.

NSB 9

The stratigraphically highest occurrence of *Plectofrondicularia seminuda* (top NSB 9) is within the Early Hemmoorian in NW Germany (Spiegler, 1974). According to King (1983, 1989), the top of NSB 9 corresponds to the top of NSP 10. NSP 10, as indicated by Diatom sp. 4 (King, 1983), is found in Borg-1.

The occurrence of *Bolboforma spiralis* in the lower part of NSB 9 may indicate a correlation with the nannoplankton zones NN 1-2, since Spiegler & Müller (1992) found common *B. spiralis* in an interval assigned to these zones. *Bolboforma rotunda/spinosa*, found higher in NSB 9, also suggests correlation with NN 2 (Spiegler & Rögl, 1992). We propose these two species as substitute markers for NSP 10.

NSB 10

Faunal assemblages of NSB 10, characterised by *Uvigerina tenuipustulata*, are known in Germany in the local Hemmoorian Stage (Spiegler, 1974; von Daniels, 1986), which corresponds to nannoplankton zones NN 3-4 (Müller *et al.*, 1979). The Arnum Formation, here considered to be the equivalent of NSB 10, has previously been correlated with the Hemmoorian (Fig. 13) using molluscan evidence (Rasmussen, 1966). In earlier German studies, the Hemmoorian was regarded to be a local Middle Miocene stage (Bettenstaedt *et al.*, 1962). However, later studies (*e.g.* Spiegler, 1986) assign an Early Miocene age to this local stage.

According to King (1983, 1989), NSB 10 corresponds to NSP 11, the top of which is defined by the highest occurrence of *Globorotalia praescitula*. In open oceanic waters, *G. praescitula* has a longer range than in the North Sea area (i.e. planktic zones N 5 up to within N 9) according to Kennett & Srinivasan (1983) and Bolli & Saunders (1985). Berggren *et al.* (1995) dated the LAD (= Last Appearance Datum) of *G. praescitula* at 11.9 Ma (i.e. within N13). The presence of *Cassigerinella chipolensis*, a substitute marker of NSP 11, in the Høruphav, Alkærsig, and Borg-1 boreholes suggests correlation with the Hemmoorian (Early Miocene; see Spiegler, 1986). However, in open oceanic waters, *C. chipolensis* has its LAD in zone N13, or at the base of N14 according to Blow (1969). Here we follow King (1989) in calibrating the top of the zones to a level within the lower part of NN5.

NSB 11

Faunal assemblages of NSB 11 correlate with Reinbekian faunas in northern Germany. The top of the Reinbekian there is assigned to NN 5, and in fact the entire Reinbekian Stage is thought to correspond to NN 5 (Müller *et al.*, 1979).

Zone NSP 12, which according to King (1989) corresponds to NSB 11, is defined by the highest occurrence of *Sphaeroidinellopsis disjuncta*. In the present study, *Bolboforma badenensis* and *B. reticulata* have their highest occurrences in this zone and are suggested as substitute markers for two new subzones of NSP 12 (see Fig. 14). In Germany, *B. reticulata* is restricted to this zone (von Daniels & Gramann, 1988). In deep-sea sediments these two *Bolboforma* species occur in nannoplankton zones NN 5-6 (Spiegler & Müller, 1992; Spiegler & Rögl, 1992, Müller & Spiegler, 1993), which agrees with King's (1989) previous correlation between NSP 12 and NN 5. However, we follow Spiegler & Gürs (1996), who dated the upper boundary of the *B. reticulata* Zone at 12.3 Ma.

NSB 12

NSB 12a faunas, including *Ceratobulimina contraria* and various subspecies of *Uvigerina semiornata* [see remark above - perhaps better referred to as formae], are found in the transition between the local Langenfeldian and Reinbekian stages stages (Fig. 13) (see Spiegler, 1974; von Daniels, 1986).

A similar fauna to that of NSB 12b is found in the lower part of the NW European Langenfeldian Stage (von Daniels *et al.*, 1990). Dinoflagellate analyses (von Daniels *et al.*, 1986) place the German fauna in the Serravallian Stage, which is also indicated by the presence of *Uvigerina pygmaea langeri*.

The top of NSB 12b was correlated by King (1983, 1989) with the top of NSP 13, the *Bolboforma clodiusi* Zone. However, in the present study the highest occurrence of *B. clodiusi* is found to be in or at the top of NSB 12c. The *B. clodiusi* Zone (NSP 13) constitutes a transition between reticulate bolboforms in the Early Miocene to flattened, spinose bolboforms in the younger part of the sequence (Qvale & Spiegler, 1989). As such, it corresponds to the *Bolboforma compressispinosa* Zone of Spiegler & von Daniels (1991). This zone was found in nannoplankton zones NN 6-7 by Spiegler & Müller (1992).

A fauna comparable with that of NSB 12c and containing in particular *Uvigerina pygmaea langenfeldensis*, is found in the lower part of the Langenfeldian (von Daniels, 1986). That part of the Langenfeldian corresponds approximately to NN Zones 7-8 (Hinsch, 1986).

According to King (1983, 1989), the top of subzone NSP 14a corresponds to the top of NSB 12c. The top of NSP 14a is defined by the highest occurrence of *Bolboforma subfragoris*. Although *B. subfragoris* has not been observed in the Danish Gram Formation, it does occur in the North Sea, associated with subzone NSB 12c. Spiegler & Müller (1992) and Müller & Spiegler (1993) correlated the top of their *Bolboforma fragoris/B. subfragoris* Zone (i.e. equivalent of the top of NSP 14a) with the upper boundary of NN 8.

NSB 13

The top of subzone NSP 14b is correlated with a level within subzone NSB 13a (King, 1983, 1989). The top of NSP 14b, defined by the first downhole occurrence of *Bolboforma metzmacheri*, corresponds to a level within NN 11a in the upper part of the Tortonian (Spiegler & Müller, 1992).

According to King (1989), the top of NSP 15a (*Neogloboquadrina acostaensis*) should correlate with the top of NSB 13a. This is not the case in the Sæd borehole where *N. acostaensis* occurs in the highest sample studied and referred to NSB 13b (Fig. 11). This species is also found at the top of a borehole at Gram (Gram-2, DGU archives no. 141.423) (Piasecki, 1980; Ersgaard *et al.*, 1977). The last occurrence of *N. acostaensis* is probably diachronous, since the event is dated at 2 Ma (i.e. within N 21) for ODP leg 94 (Hooper & Weaver, 1987), and older than 5.5 Ma (i.e. within N 17) for ODP leg 104 (Spiegler & Jansen, 1989). In Germany, *N. acostaensis* is thought to have its last occurrence at the Miocene/Pliocene boundary, at the top of N 17 (Spiegler, 1986).

Subzone NSB 13b, as defined by the highest occurrence of *Uvigerina venusta saxonica*, spans the Miocene-Pliocene boundary according to King (1989). Von Daniels (1986) stated that the youngest occurrence of species of *Uvigerina* was influenced by a regressional phase, and that their last occurrence might be diachronous. In Germany, their last occurrence is situated in the Gramian Stage (von Daniels, 1986). Evidently, this is also the case in the Sæd borehole where species of *Uvigerina* are absent from the NSB 13b interval, referred to the Syltian Stage on molluscan evidence (Rasmussen, pers. comm., 1993).

CONCLUSIONS

The established North Sea zonations (King, 1983, 1989) have been applied in the present study, and the dense sampling intervals have made it possible to subdivide these zones further, *e.g.* a few benthic foraminiferal zones. In addition, various substitute markers have been introduced both for benthic and planktic zones (Fig. 14). In the Early Miocene, *Bolboforma rotunda* is found in the upper part of NSB 9 and is here suggested as a substitute marker for planktic zone NSP 10. The Early Miocene benthic zone NSB 10 has been subdivided, with the highest occurrence of *Loxostomum sinuosum* marking the top of the new subzone NSB 10I. *Cassigerinella chipolensis* is suggested as representative for the planktic zone NSP 11. The Middle Miocene NSB 11 zone has been subdivided into two, with an elphidiid/nonioniid fauna introduced as a marker of subzone NSB 11I. The highest occurrence of *Bolboforma badenensis* is observed approximately at the top of this new benthic subzone NSB 11I, and *B. badenensis* is proposed as a marker for a new planktic subzone, NSP 12I. *Bolboforma reticulata* is suggested as a substitute marker for the top of the planktic zone NSP 12, equalling the top of subzone NSP 12II as defined in the present study.

As here understood, the highest occurrence of *Ceratobulimina contraria* marks the top of NSB 12a; this species is here introduced as a substitute marker for this zone. NSB 12b and NSP 13 are represented in the Danish Miocene, but the succeeding NSB 12c subzone is poorly developed and planktic subzone NSP 14a has not been identified. *Ehrenbergina pupa* is suggested as a substitute marker for NSB 12c. NSB 13a, NSB 13b, NSP 14b, and NSP 15a are also present in the boreholes studied.

The chronostratigraphic placement of all the zones has been reinterpreted in the light of more recent publications (see Fig. 13).

Palaeoenvironmental data obtained from a study of Miocene foraminifera suggest several oscillations in water depth to have occurred, which, to some degree, proved to be correlatable with sea level changes as deduced from the sequence-stratigraphic framework for the Danish North Sea area (Michelsen *et al.*, 1995, 1998).

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Benthic foraminifera
Alliatina spp.
Ammonia beccarii (Linné, 1758) (Pl. 2, fig. 6)
Asterigerina frankei ten Dam & Reinhold, 1941 (Pl. 1, fig. 5)
Asterigerina staeschei ten Dam & Reinhold, 1941 (Pl. 3, fig. 6)
Astrononion perfossum (Clodius, 1922) (Pl. 4, fig. 1)
Bolivina imporcata Cushman & Renz, 1944 (Pl. 2, fig. 2)
Brizalina antiqua (d'Orbigny, 1846)
Bulimina aculeata d'Orbigny, 1826
Bulimina dingdenensis Batjes, 1958 (Pl. 2, fig. 1)
Bulimina elongata d'Orbigny, 1846 (Pl. 1, fig. 6)
Bulimina sp.
Cancris auriculus (Fichtel & Moll, 1803)
Cassidulina laevigata d'Orbigny, 1826 (Pl. 5, fig. 6)
Ceratobulimina contraria (Reuss, 1851) (Pl. 3, fig. 7)
Cribrononion heteroporum (Egger, 1857) (Pl. 3, fig. 1)
Discorbis mira Cushman, 1922 (*sensu* de Meuter, 1980)
Ehrenbergina pupa (d'Orbigny, 1839) (Pl. 4, fig. 6)
Elphidiella minuta (Reuss, 1865) (Pl. 2, fig. 7)
Elphidium antoninum (d'Orbigny, 1846) (compare Pl. 5, fig. 4)
Elphidium inflatum (Reuss, 1861) (Pl. 3, fig. 3)
Elphidium ungeri (Reuss, 1850) (Pl. 2, fig. 8)
Epistominella oveyi (Bhatia, 1955)
Eponides pygmaea (von Hantken, 1875)
Glandulina morsumensis van Voorthuysen, 1962 (Pl. 5, fig. 7)
Globocassidulina perforata Spiegler, 1974
Globocassidulina subglobosa (Brady, 1881) (Pl. 3, fig. 9)
Heterolepa dutemplei (d'Orbigny, 1846)
Heterolepa tenella (Reuss, 1865)
Hoeglundina elegans (d'Orbigny, 1826) (Pl. 3, fig. 8)
Loxostomum sinuosum (Cushman, 1936) (Pl. 1, fig. 4)
Massilina haidingeri (d'Orbigny, 1846) (Pl. 2, fig. 5)
Melonis affine (Reuss, 1851) (Pl. 5, fig. 2)
Nonion boueanum (d'Orbigny, 1846) (Pl. 4, fig. 9)
Nonion granosum (d'Orbigny, 1846) (Pl. 3, fig. 2)
Nonion roemeri Cushman, 1936
Oridorsalis umbonatus (Reuss, 1851)
Pararotalia canui (Cushman, 1928) (Pl. 1, fig. 1)
Plectofrondicularia advena (Cushman, 1923)
Plectofrondicularia seminuda (Reuss, 1851) (Pl. 1, fig. 2)
Pullenia bulloides (d'Orbigny, 1846)
Quinqueloculina spp.
Rolfina arnei Laursen, 1994
Siphotextularia sculpturata (Cushman & ten Dam, 1947) (Pl. 5, fig. 3)
Sphaeroidina bulloides d'Orbigny, 1826 (Pl. 4, fig. 3)
Spiroplectammina deperdita (d'Orbigny, 1846)
Textularia gramen d'Orbigny, 1846 (Pl. 5, fig. 1)
Trifarina bradyi Cushman, 1923
Trifarina gracilis (Reuss, 1851)
Trifarina gracilis (spinous) (Pl. 4, fig. 5)
Trifarina tenuistriata (Reuss, 1870) (Pl. 2, fig. 3)
Uvigerina acuminata Hosius, 1895
Uvigerina germanica (Cushman & Edwards, 1938)
Uvigerina pygmaea langenfeldensis von Daniels & Spiegler, 1977 (Pl. 4, fig. 4)
Uvigerina p. langeri von Daniels & Spiegler, 1977 (Pl. 4, fig. 2)
Uvigerina s. semiornata d'Orbigny, 1846 (Pl. 3, fig. 5)
Uvigerina s. brunnensis Karrer, 1877
Uvigerina s. saprophila von Daniels & Spiegler, 1977 ?
Uvigerina tenuipustulata van Voorthuysen, 1950
Uvigerina venusta deurnensis de Meuter & Laga, 1976 (Pl. 4, fig. 7)
Uvigerina v. saxonica von Daniels & Spiegler, 1977
Valvulineria complanata (d'Orbigny, 1846) (Pl. 1, fig. 3)

Planktic foraminifera
Cassigerinella chipolensis (Cushman & Ponton, 1932) (Pl. 2, fig. 4)
Globorotalia praescitula Blow, 1959
Neogloboquadrina acostaensis (Blow, 1959)

Bolboforma
Bolboforma badenensis Szczechura, 1982
Bolboforma clodiusi von Daniels & Spiegler, 1974 (Pl. 4, fig. 8)
Bolboforma metzmacheri (Clodius, 1922) (Pl. 5, fig. 5)
Bolboforma reticulata von Daniels & Spiegler, 1974 (Pl. 3, fig. 4)
Bolboforma rotunda/spinosa von Daniels & Spiegler, 1974
Bolboforma spiralis von Daniels & Spiegler, 1974
Bolboforma sp. Spiegler & von Daniels, 1991

Diatoms
Diatom sp. 3 King, 1983
Diatom sp. 4 King, 1983

Table 3. Selected species of foraminifera and *Bolboforma* found in the Danish Miocene material are arranged alphabetically in the following list.

PLATE 1

Fig. 1. *Pararotalia canui* (Cushman, 1928), Vejle Fjord Formation, Høruphav (sample 74.30-74.80 m), x 400.

Fig. 2. *Plectofrondicularia seminuda* (Reuss, 1851), marker species of NSB9, 'Klintinghoved Formation', Høruphav (sample 50.90-51.35 m), x 60.

Fig. 3. *Valvulineria complanata* (d'Orbigny, 1846), Arnum Formation, Høruphav (sample 48.90-49.10 m), x 300.

Fig. 4. *Loxostomum sinuosum* (Cushman, 1936), marker species of NSB10I, Arnum Formation, Glejbjerg (DGU archives no. 122.211), sample 79.5-80.0 m, x 300.

Fig. 5. *Asterigerina frankei* ten Dam & Reinhold, 1941, Arnum Formation, Høruphav (sample 48.90-49.10 m), x 165.

Fig. 6. *Bulimina elongata* d'Orbigny, 1846, Vestervang, x 235.

PLATE 1

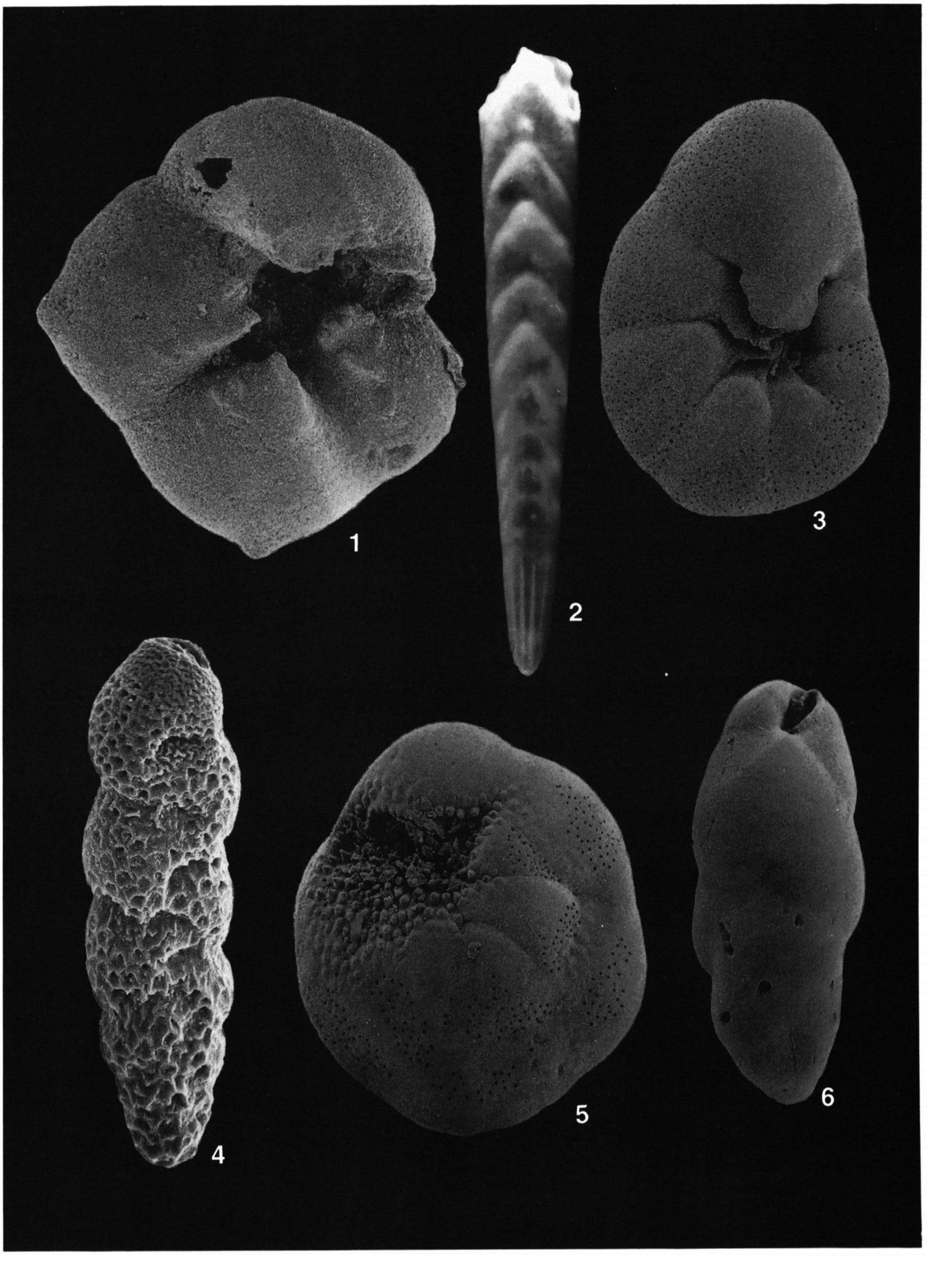

PLATE 2

Fig. 1. *Bulimina dingdenensis* Batjes, 1958, substitute marker species of NSB 10II, Arnum Formation, Alkærsig, 29.0 m, x 462.
Fig. 2. *Bolivina imporcata* Cushman & Renz, 1944, Arnum Formation, Alkærsig, 53.0 m, x 215.
Fig. 3. *Trifarina tenuistriata* (Reuss, 1870), Arnum Formation, Høruphav (sample 48.90-49.10 m), x 200.
Fig. 4. *Cassigerinella chipolensis* (Cushman & Ponton, 1932), substitute marker species of NSP 11, Arnum Formation, Alkærsig, 65.5 m, x 300.
Fig. 5. *Massilina haidingeri* (d'Orbigny, 1846), Arnum Formation, Hodde-1, 27.50 m, x 60.
Fig. 6. *Ammonia beccarii* (Linné, 1758), Arnum Formation, Alkærsig, 57.0 m, x 90.
Fig. 7. *Elphidiella minuta* (Reuss, 1865), Arnum Formation, Alkærsig, 60.0 m, x 200.
Fig. 8. *Elphidium ungeri* (Reuss, 1850), Arnum Formation, Alkærsig, 51.0 m, x 200.

PLATE 2

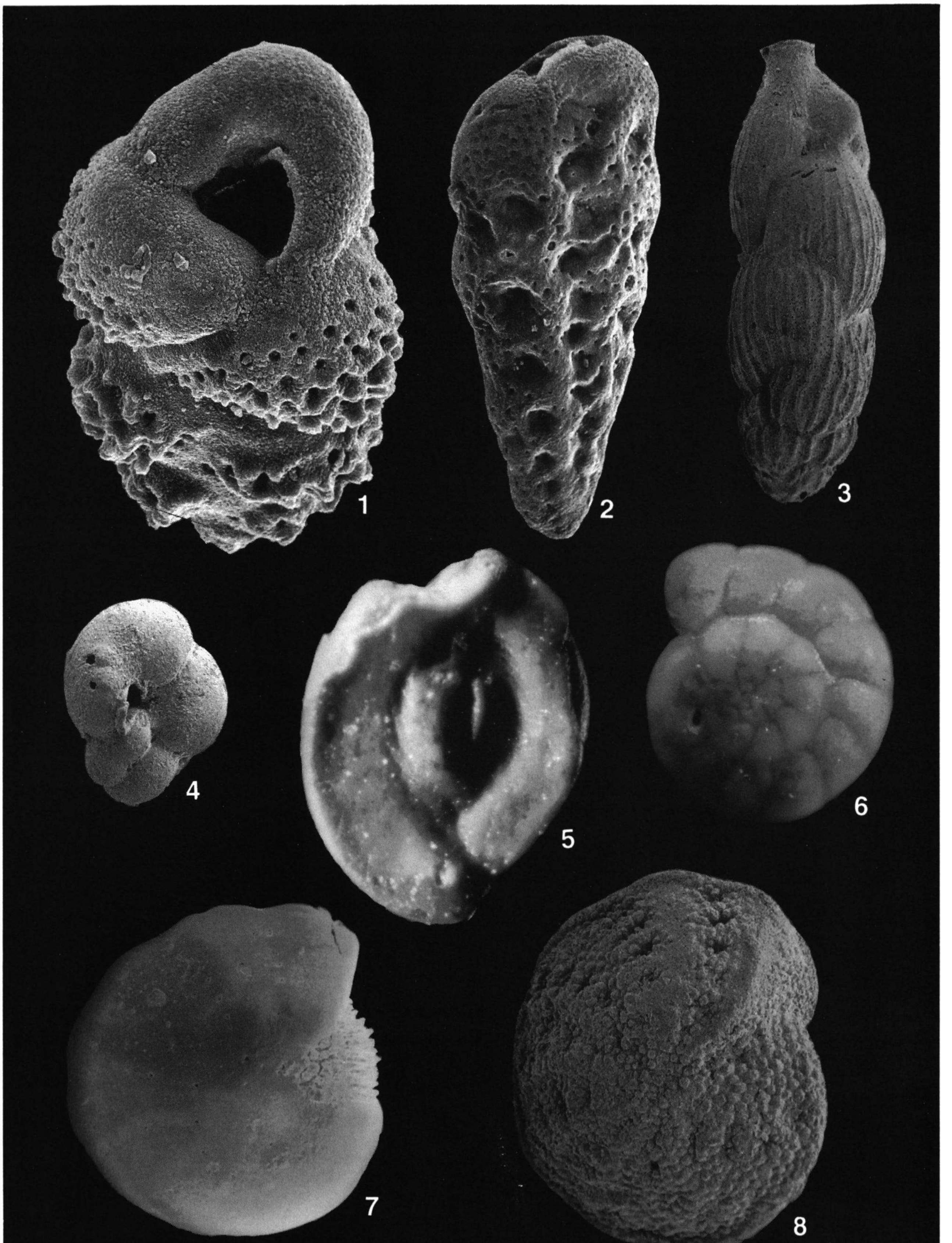

PLATE 3

Fig. 1. *Cribrononion heteroporum* (Egger, 1857), Arnum Formation, Alkærsig, 53.0 m, x 300.
Fig. 2. *Nonion granosum* (d'Orbigny, 1846), Arnum Formation, Høruphav (sample 48.90-49.10 m), x 400.
Fig. 3. *Elphidium inflatum* (Reuss, 1861), Hodde Formation, Gram-1, 34.70-35.00 m, x 90.
Fig. 4. *Bolboforma reticulata* von Daniels & Spiegler, 1974, substitute marker of NSP 12II, Hodde Formation, Gram-1, 32.30-32.70 m, x 500.
Fig. 5. *Uvigerina s. semiornata* d'Orbigny, 1846, Hodde Formation, Gram-1, 31.95-32.30 m, x 135.
Fig. 6. *Asterigerina staeschei* ten Dam & Reinhold, 1941, marker species of NSB 11II, Hodde Formation, Gram-1, 30.00-30.50 m, x 300.
Fig. 7. *Ceratobulimina contraria* (Reuss, 1851), substitute marker species of NSB 12a, Hodde Formation, Gram-1, 31.95-32.30 m, x 300.
Fig. 8. *Hoeglundina elegans* (d'Orbigny, 1826), Grundfør, x 60.
Fig. 9. *Globocassidulina subglobosa* (Brady, 1881), A-1, 2640'-2670', x 300.

PLATE 3

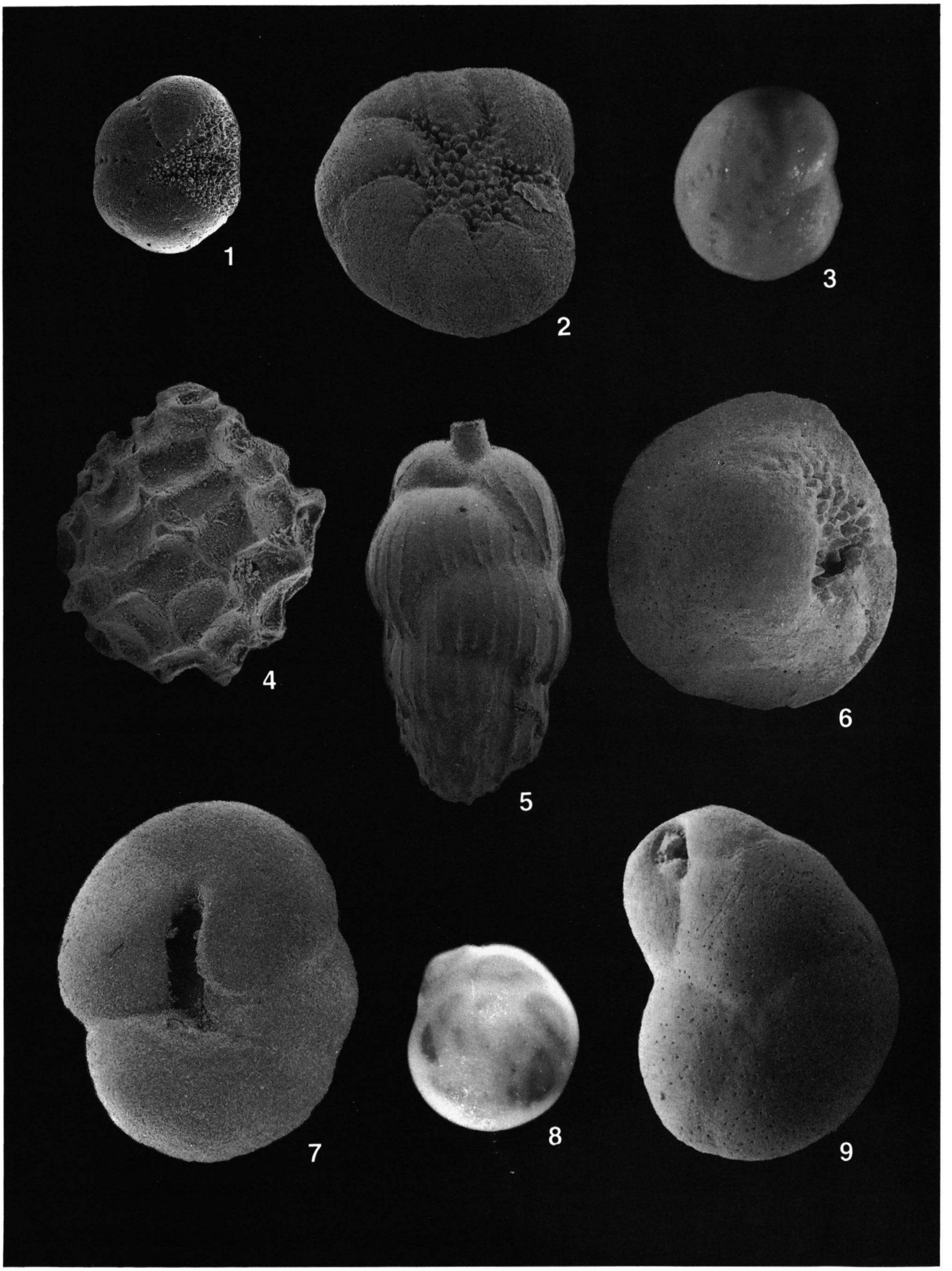

PLATE 4

Fig. 1. *Astrononion perfossum* (Clodius, 1922), Hodde Formation, Gram-1, 30.00-30.50 m, x 300.
Fig. 2. *Uvigerina pygmaea langeri* von Daniels & Spiegler, 1977, marker species of NSB 13a, Gram Formation, Gram-1, 15.10-15.55 m, x 165.
Fig. 3. *Sphaeroidina bulloides* d'Orbigny, 1826, Gram Formation, Gram-1, 5.30-5.70 m, x 300.
Fig. 4. *Uvigerina pygmaea langenfeldensis* von Daniels & Spiegler, 1977, A-1, 4290'-4320', x 133.
Fig. 5. *Trifarina gracilis* (spinous), Gram Formation, Lille Tønde, 51.75-52.25 m, x 115.
Fig. 6. *Ehrenbergina pupa* (d'Orbigny, 1839), substitute marker species of NSB 12c, Gram Formation, Gram-1, 13.50-14.00 m, x 60.
Fig. 7. *Uvigerina venusta deurnensis* de Meuter & Laga, 1976, Gram Formation, Gram-1, 15.10-15.55 m, x 300.
Fig. 8. *Bolboforma clodiusi* von Daniels & Spiegler, 1974, marker species of NSP 13, Gram Formation, Gram-1, 20.50-21.00 m, x 500.
Fig. 9. *Nonion boueanum* (d'Orbigny, 1846), Gram Formation, Gram-1, 5.30-5.70 m, x 165.

PLATE 4

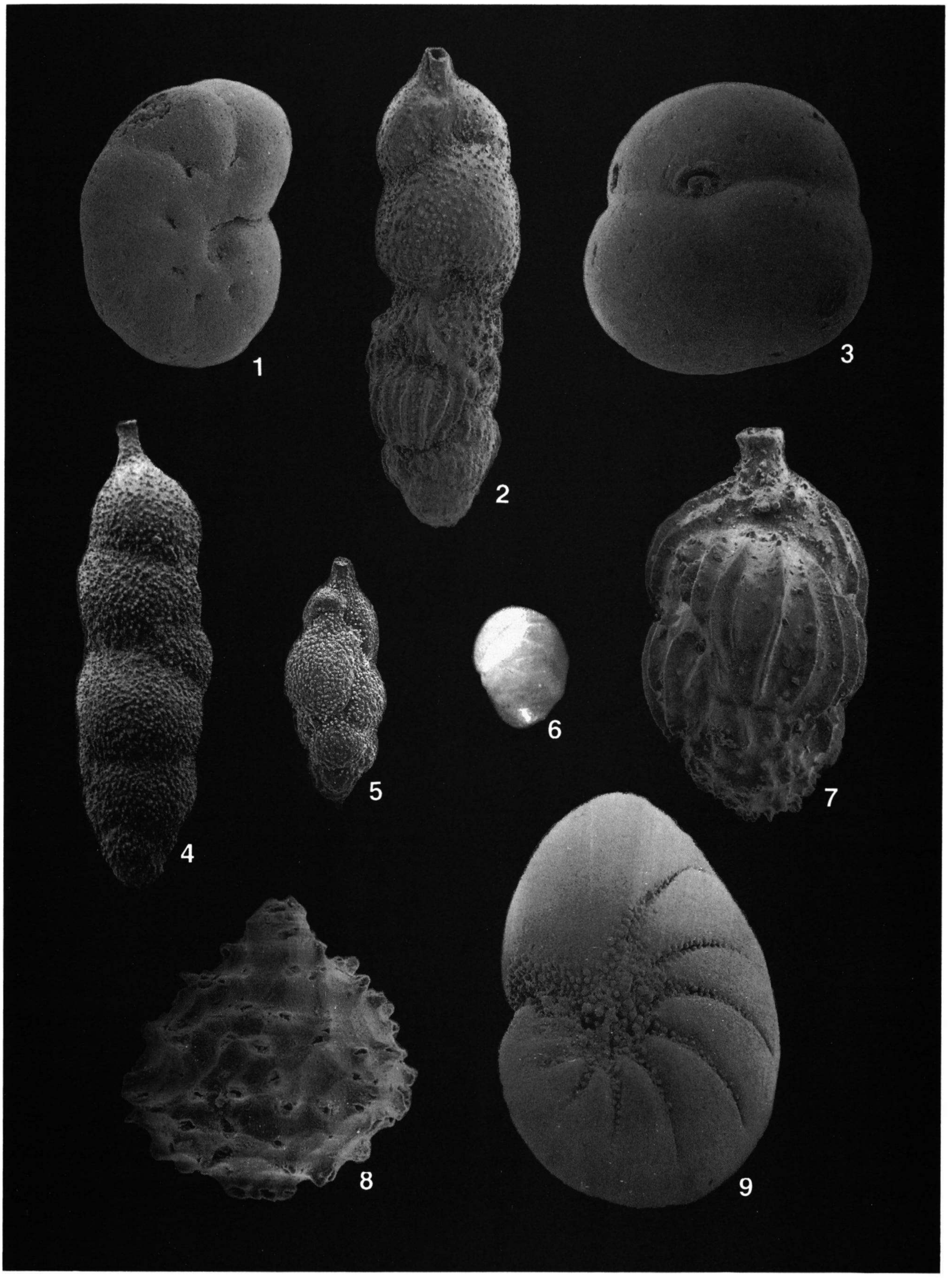

PLATE 5

Fig. 1. *Textularia gramen* d'Orbigny, 1846, Gram Formation, Gram-1, 5.70-6.10 m, x 60.
Fig. 2. *Melonis affine* (Reuss, 1851), Gram Formation, Gram-1, 15.10-15.55 m, x 200.
Fig. 3. *Siphotextularia sculpturata* (Cushman & ten Dam, 1947), Gram Formation, Gram-1, 5.30-5.70 m, x 60.
Fig. 4. *Elphidium cf. antonium*, Gram Formation, Sæd, 92.25-92.70 m, x 200.
Fig. 5. *Bolboforma metzmacheri* (Clodius, 1922), marker species of NSP 14b, Gram Formation, Gram-1, 9.90-10.30 m, x 400.
Fig. 6. *Cassidulina laevigata* d'Orbigny, 1826, Gram Formation, Gram-1, 15.10-15.55 m, x 300.
Fig. 7. *Glandulina morsumensis* van Voorthuysen, 1962, Gram Formation, Sæd, 90.30-91.00 m, x 60.

PLATE 5