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Late Younger Dryas to Holocene palaeoenvironments of the southern Kattegat, Scandinavia

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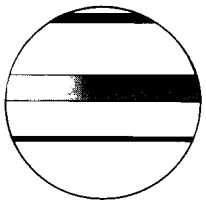

Abstract: Palaeoenvironmental changes since the late Younger Dryas are reconstructed in the southern Kattegat (Scandinavia) and provide a basis for correlating the whole of the North Sea-Skagerrak-Kattegat-Baltic region. The foraminiferal content of seven piston and three vibrocores were analysed. Radiocarbon dates were obtained from four of the cores. Relatively warm water masses occurred in the shallow areas of the Kattegat during the late Younger Dryas and early Preboreal, while cold, arctic/subarctic water masses occurred in deeper parts of the Kattegat and Skagerrak. Full interglacial temperature conditions developed in the southern Kattegat at 9600 BP. A sea-level rise is recorded at 9600–8200 BP, a period during which the Skagerrak-Kattegat area experienced a gradual warming. A change in sedimentological and environmental conditions occurred in the southern Kattegat at around 8000 BP, reflecting the opening of a connection to the Baltic and corresponding hydrographic changes. The modern general circulation pattern of the area was established after this event. A further rise in sea level is recorded after 8000 BP. A mid-Holocene alteration in hydrographic and sedimentation pattern in the area is marked by the reappearance of *Nonionellina labradorica* in the southern Kattegat. This alteration, previously dated to 4000 BP, is redated to 5500 BP and is interpreted as reflecting the well-defined late-Atlantic cooling of the North Atlantic region resulting in changed inflow/outflow pattern of water masses in the Kattegat.

Key words: Younger Dryas, Holocene, foraminifera, radiocarbon-dating, palaeoenvironments, hydrography, Kattegat, North Sea, Baltic.

Introduction

Younger Dryas to Holocene marine sediments from the Skagerrak/Kattegat area have been extensively studied in the past. The results reveal both the local palaeoenvironmental development of the area, and also have potential for correlation to the North Atlantic region. This is of special interest because the North Atlantic circulation pattern is closely linked to the global climatic state. Unfortunately, Holocene sedimentary records in the North Atlantic often have rather poor resolution due to low sedimentation rates.

This study presents new information on the late Younger Dryas – Holocene palaeoenvironmental development of the southern Kattegat, mainly based on foraminiferal assemblages supported by radiocarbon-dating (Figure 1). The study provides new data on local conditions and the study also supports the palaeoenvironmental and palaeoceanographic interpretations of the recently recovered, high-resolution Skagen 3/4 core (Figure 1) situated at the Skagerrak-Kattegat transition. The Skagen 3/4 core, with 115 m of Holocene sediments, is a key core for the area. It displays Holocene environmental changes which seem to be correlatable to the North Atlantic region (Conradsen and Nielsen, in press). Thus the present study further substantiates the late Younger Dryas – Holocene palaeoceanographic and palaeoenvironmental history of the whole Skagerrak-Kattegat area and therefore presumably also the North Atlantic.

The southern Kattegat in the Holocene

The basin shape of the Kattegat was formed during the Weichselian glaciation and subsequent deglaciation (Nielsen and Konradi, 1990; Gyldenholm *et al.*, 1993) and at present has a mean water depth of 23 m (Figure 1). Around the Pleistocene/Holocene transition the Skagerrak-Kattegat formed a large fjord-like system, later gradually widening due to eustatic sea-level rise (Jelgersma, 1979; Stabell and Thiede, 1986; Thiede, 1987). Owing to northward migration of the North Atlantic polar front, intrusion of Atlantic water created boreal, full interglacial conditions in the area around 9600 BP (Peacock and Harkness, 1990; Conradsen and Nielsen, in press and herein). Close to the Boreal/Atlantic transition a connection opened through the Danish Straits to the Baltic, which ended the Ancylus stage of the Baltic (Björck, in press). This was also approximately the time of the opening of

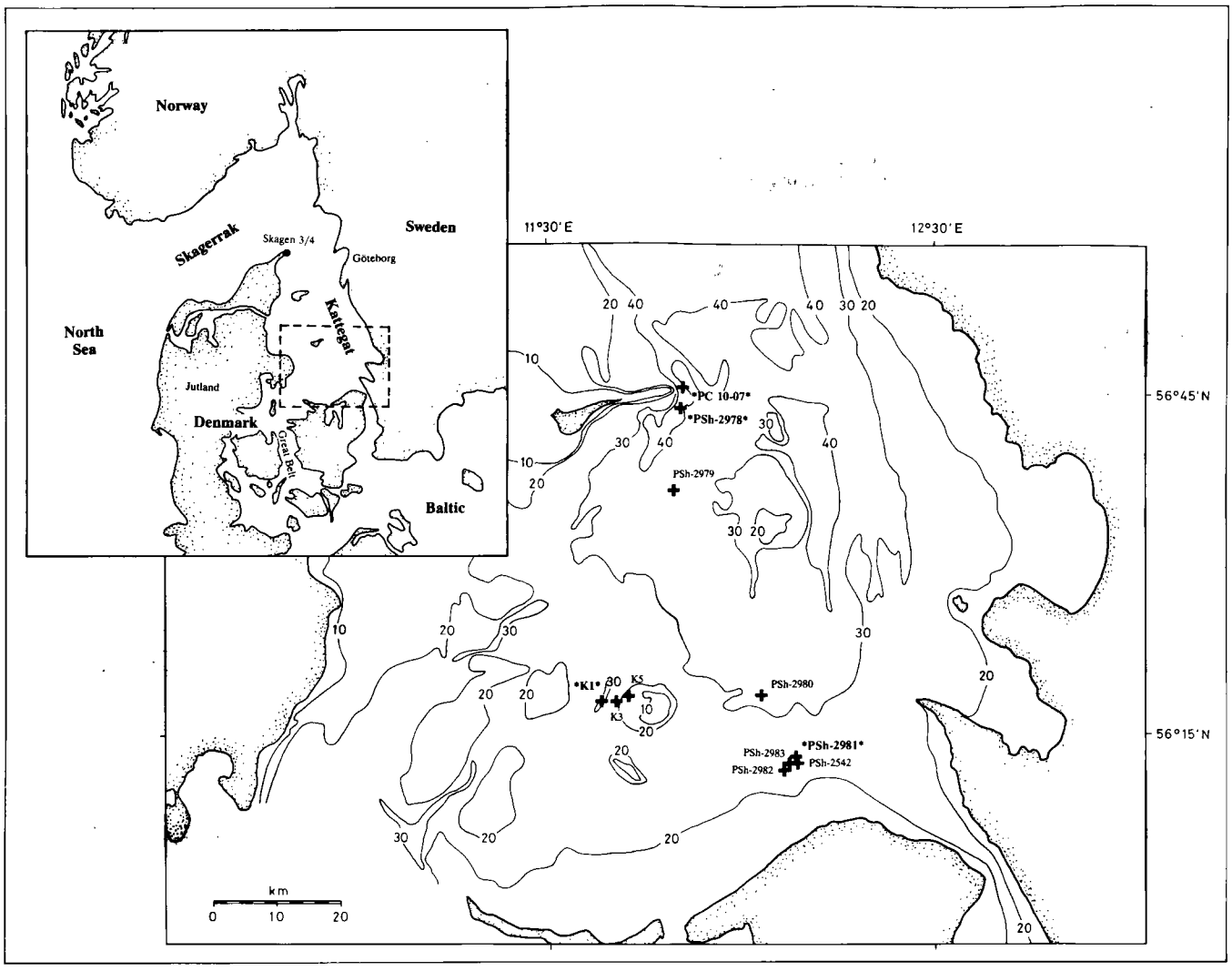

Figure 1 Location of investigated cores in the southern Kattegat. Cores marked with asterisks are described in this study.

the English Channel (Jelgersma, 1979). At that time, the prevailing, hydrographic circulation pattern of the North Sea-Skagerrak-Kattegat area was established. This major hydrographic and environmental change, referred to below as the 8000 BP change, was probably not contemporaneous over the whole region (see below). The balance between isostatic rebound and eustatic sea-level rise resulted in maximum transgression during the Atlantic with a subsequent small regression. Several modifications of the hydrography have taken place since the 8000 BP change, the most important previously dated to 4000 BP (Nordberg and Bergsten, 1988; Nordberg, 1989; 1991) but redated to 5500 BP in the present study.

The modern Skagerrak and Kattegat can be regarded as a large estuarine system between the North Sea and the Baltic. The general hydrography of the southern Kattegat is determined by intermittently outflowing, low-salinity (15–30‰) surface water masses from the Baltic and inflowing, high-salinity (30–35‰) bottom water masses from the Skagerrak. A pronounced halocline is developed at 10–20 m water depth. The current pattern is generally strongly dependent on meteorologic conditions and on seasonal variations (Dietrich, 1951; Svansson, 1975; 1984; Stigebrandt, 1983).

Holocene sediments in the southern Kattegat most commonly rest on locally very thick, possibly late Weichselian water-laid deposits (up to 100 m to the southeast). The Holocene deposits are very unevenly distributed in the area. They are absent in some places and generally do not exceed 10 m in thickness. Hydrographic changes during the Holocene also altered the sediment fluxes and depositional centres in the area (Nordberg and Bergsten, 1988; Nordberg, 1989; 1991; Bergsten and Nordberg, 1992; Gyldenholm *et al.*, 1993).

Material and methods

Seven pistoncores (PSh-2978–PSh-2983 and PC 10–07, length 1.1–7.6 m) and three vibrocores (K1, K3, K5, *c.* 6 m) were investigated (Figure 1; Table 1). They were retrieved on cruises with the Russian vessel *Professor Shtockman* in 1992 and R.V. *Svanic* of Göteborg, Sweden, in 1990. Sample slices of 2–5 cm were analysed for foraminifera following the laboratory procedures of Feyling-Hanssen *et al.* (1971), analysing the 0.1–1.0 mm fraction and counting at least 300 specimens per sample.

Radiocarbon datings were carried out in the AMS laboratory at the Institute of Physics and Astronomy, University of Aarhus, as described by Andersen *et al.* (1989) (Table 2), and reported in accordance with Stuiver and Polach (1977). The datings were performed on shell material of molluscs and in one case of foraminifera. All dates presented in the study are corrected for a reservoir effect of 400 years, according to standard procedure for Danish waters (Krog and Tauber,

Table 1 Investigated cores from the southern Kattegat.

Core	Longitude (°E)	Latitude (°N)	Water depth (m)	Recovery (cm)
PSh-2978	11°50.75'	56°43.85'	*c.* 42	471
PSh-2979	11°49.62'	56°38.61'	*c.* 32	405
PSh-2980	12°03.10'	56°18.71'	*c.* 30	107
PSh-2981	12°08.59'	56°13.90'	*c.* 24	426
PSh-2982	12°07.16'	56°12.04'	*c.* 22	135
PSh-2983	12°07.47'	56°12.69'	*c.* 24	267
K1	11°38.31'	56°18.14'	*c.* 30	600
K3	11°40.67'	56°18.09'	*c.* 21	600
K5	11°42.45'	56°18.60'	*c.* 17	320
PC 10-07	11°51.24'	56°45.29'	*c.* 50	760

1974). Foraminiferal assemblage zones were established according to Hedberg (1976). Detailed descriptions of all the zones are not provided here. The terms 'lusitanian, boreal, subarctic and arctic' for bioclimatic foraminiferal zonations are defined according to Feyling-Hanssen (1955) (based on molluscs) slightly modified by Seidenkrantz and Knudsen (1993). Chronozones were defined according to Mangerud *et al.* (1974).

Chronological framework

Holocene palaeoenvironments of the Skagerrak-Kattegat have previously been widely studied (for example Lange, 1956; Jørgensen *et al.*, 1981; Cato *et al.*, 1982; Fält, 1982; Björklund *et al.*, 1985; Knudsen and Nordberg, 1987; Nordberg and Bergsten, 1988; Nordberg, 1989; 1991; Christiansen *et al.*, 1993; Conradsen and Nielsen, in press). However, many of these studies suffer from a lack of sufficient chronological control.

The established chronology of the present cores is mainly based on radiocarbon dates (Table 2). At a number of levels in the studied cores, mollusc shells were only present as fragments or were even absent, but were nevertheless mostly considered *in situ*, which was the selection criteria. Possible influences of reworking, bioturbation or contamination of the dated material are further discussed below in connection with the palaeoenvironmental interpretations. The chronology is supported by local foraminiferal stratigraphy (mainly from Nagy and Qvale, 1985; Nordberg and Bergsten, 1988).

Four cores, probably representing the whole late Younger Dryas – Holocene period and all radiocarbon-dated (Table 2; Figure 2), have been selected to demonstrate the Holocene palaeoenvironmental development of the area (Figures 3–6). They are discussed below in chronological order. The results obtained from the remaining cores generally supported the interpretations.

PC 10–07 (Figure 3)

PC 10–07 possibly contains a complete mid-Younger Dryas – Holocene sequence. Two dates were obtained from PC 10–07, showing that the lowermost part of the core (*c.* 300–760 cm) is of Younger Dryas/Preboreal/Boreal age. Post-8000 BP sediments are recorded from *c.* 0–300 cm.

PSh-2981 (Figure 4)

Five dates were obtained from this core. These showed that

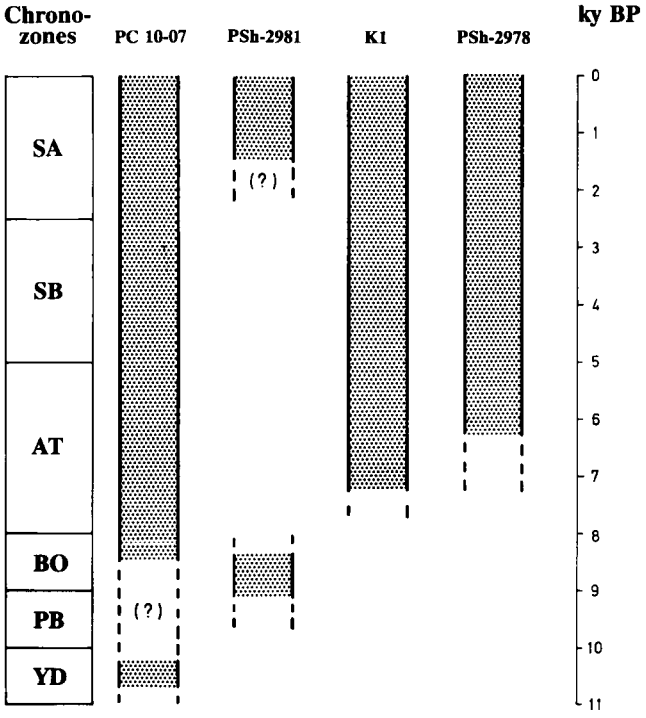

Figure 2 Chronostratigraphic allocation of the marine sediments of the cores described in this study. The chronology is based on the radiocarbon dates of Table 2 and supported by local foraminiferal stratigraphy. SA = Subatlantic, SB = subboreal, AT = Atlantic, BO = Boreal, PB = Preboreal, YD = Younger Dryas.

Table 2 Radiocarbon dates from the cores of the study (Res. corr. = Reservoir corrected; B.mar = *Bulimina marginata*; H.bal = *Hyalinea balthica*)

Core	Level below sea-floor (cm)	Sample ID	Material	^{14}C age (BP)	Res. corr. ^{14}C age (BP)
PSh-2978	125–130	AAR-1330	Mollusc frags.	5030 ± 90	4630 ± 90
PSh-2978	147–152	AAR-1574	B.mar + H.bal.	5420 ± 90	5020 ± 90
PSh-2978	169–174	AAR-1331	Mollusc frags.	900 ± 80	500 ± 80
PSh-2981	1–4	AAR-997	Mollusc frags.	1455 ± 95	1055 ± 95
PSh-2981	6–10	AAR-998	Mollusc frags.	1835 ± 95	1435 ± 95
PSh-2981	17–21	AAR-999	Mollusc frags.	6025 ± 85	5625 ± 85
PSh-2981	80–84	AAR-1086	Mollusc frags.	9340 ± 160	8940 ± 160
PSh-2981	309–313	AAR-1088	*Cardium* shell	9030 ± 100	8630 ± 100
K1	185–188	AAR-1329	Mollusc frags.	4880 ± 110	4480 ± 100
K1	245–248	AAR-1332	Mollusc frags.	6780 ± 120	6380 ± 120
PC 10-07	320–324	AAR-1576	Mollusc frags.	8840 ± 75	8440 ± 75
PC 10-07	665–670	AAR-1575	*Arctica islandica*	11050 ± 100	10650 ± 100

the lowermost *c.* 400 cm were deposited in Preboreal-Boreal times and that only the top *c.* 20–25 cm is younger than the Boreal.

K1 (Figure 5)

Two samples were dated from core K1. The total marine sequence (0–450 cm) is interpreted to have been deposited after 8000 BP. This sequence rested on coarse-grained, probably fluvial sediments, which were presumably deposited in pre-8000 BP times as part of the early-Holocene drainage of the Baltic (K1 is situated in the northern extension of the Weichselian-Holocene fluvial channel system of the Great Belt (Winn, 1974; Björck, in press)). The foraminiferal assemblages in the lowermost marine sediments reflect fairly deep water conditions (Conradsen, 1993). Sediments representing the early part of the marine transgression are therefore missing. This suggests an age slightly younger than 8000 BP for the bottom of the marine sequence.

PSh-2978 (Figure 6)

Three samples were dated in this core, which represents a continuous, mid- to late Holocene sequence. The lowermost date is clearly out of place and considered a result of contamination, either during sampling or in the laboratory (only one small mollusc fragment was found and dated in the sample). The bottom of the core must be younger than the Boreal, owing to the presence of *Hyalinea balthica* (Schroeter) (Nagy and Qvale, 1985).

Palaeoenvironments

Palaeoenvironmental changes are recorded in the southern Kattegat at the transition from de-glacial to full-interglacial conditions. Furthermore, all of the investigated cores, which included the 8000 BP level and hence the major hydrographic change described above, displayed changes in sediments and sedimentation rates at that level. The palaeoenvironments of the area are therefore divided into three periods. These are the period before the establishment of full-interglacial conditions (late Younger Dryas–early Preboreal (before 9600 BP), including the Pleistocene-Holocene boundary according to the standard chronology of Mangerud *et al.* (1974)), and Holocene pre- and post-8000 BP periods.

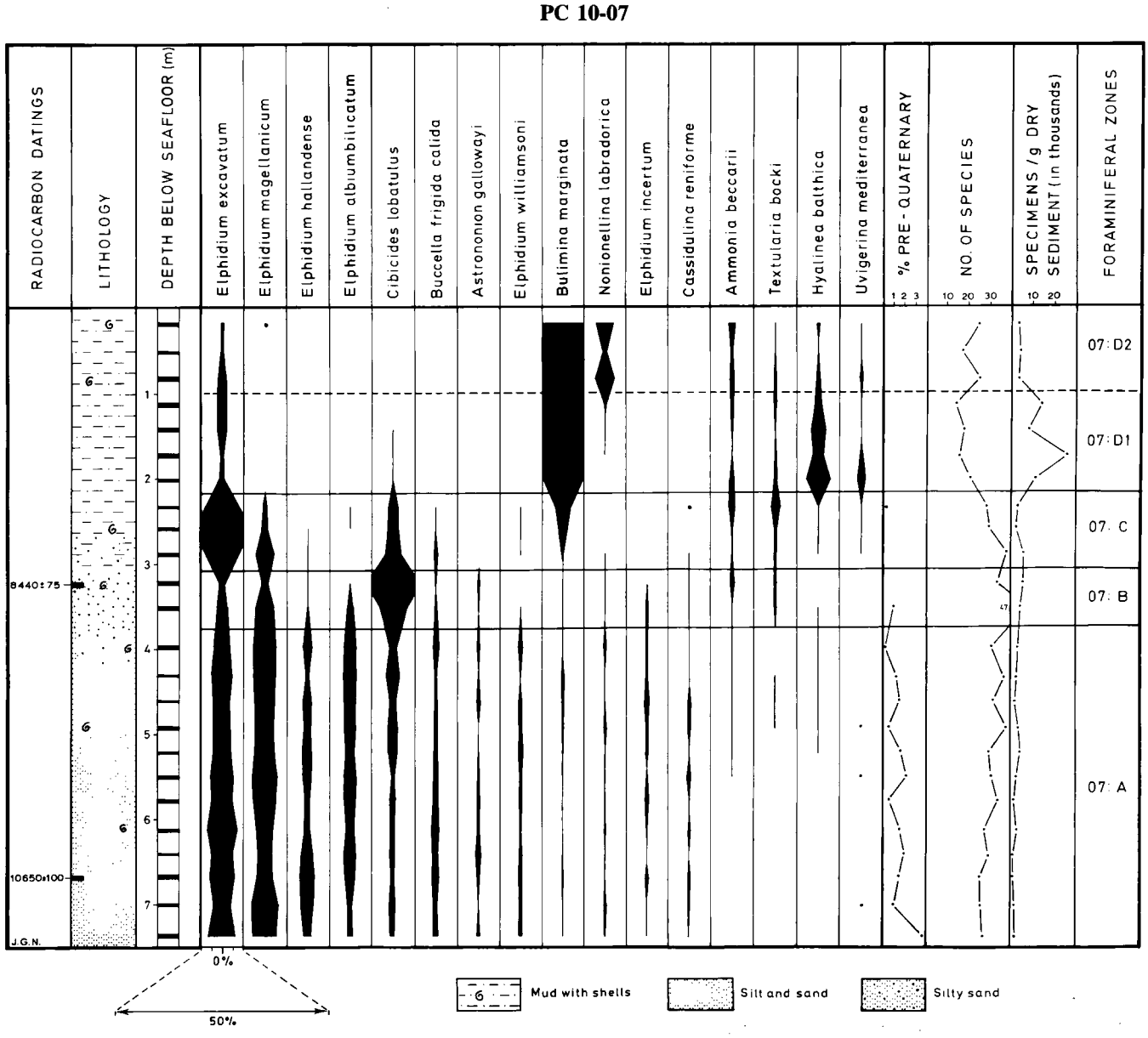

Figure 3 Foraminiferal range chart of selected species in core PC 10–07.

Younger Dryas – early Preboreal

Records and interpretation

Sediments representing the Younger Dryas – early Preboreal were only found in the silts and sands corresponding to foraminiferal zones 07:A–07:B of PC 10–07 (Figure 3). The shallow-water, low-salinity foraminiferal assemblage of zone 07:A is a mixture of mainly boreal species, e.g., *Elphidium albiumbilicatum* (Weiss), *Elphidium magellanicum* (Heron-Allen and Earland) and *Elphidium williamsoni* (Haynes), and arctic/subarctic, e.g., *Elphidium hallandense* Brotzen and *Astrononion gallowayi* Loeblich and Tappan (Feyling-Hanssen, 1983; Seidenkrantz and Knudsen, 1993). It should be noted, however, that benthic foraminiferal ecology in shallow arctic/subarctic regions is not fully understood. The presence of lusitanian species (e.g., *H. balthica*), low frequencies of pre-Quaternary specimens and generally somewhat worn specimens indicates that the assemblages may be influenced by reworking. However, the radiocarbon date of zone 07:A (10650 ± 100 BP) was performed on a large shell fragment of the bivalve *Arctica islandica* Linné and is considered *in situ*.

Discussion

The present data confirm that boreo-arctic foraminiferal assemblages occurred in the area in the late Younger Dryas/early Preboreal (zone 07:A, Figure 3). Zone 07:A represents similar environmental conditions to the shallow-marine, arctic-temperate Younger Dryas assemblages found in the southern Kattegat by Bergsten and Nordberg (1992) and the shallow-marine, boreo-arctic transitional assemblages recorded in the Göteborg area around 10200–9500 BP (Knudsen, 1982; Bergsten and Dennegård, 1988; Bergsten, 1991; 1994). Accordingly, all late Younger Dryas/early Preboreal records from shallow-water environments in the Kattegat seem to have boreo-arctic – boreal foraminiferal assemblages.

Recently, Bergsten (1994) interpreted a major palaeoclimatic change at 10 200 BP in the Göteborg area, based on shallow water foraminiferal assemblages. Transitional assemblages were recorded 10200–9500 BP (Bergsten, 1991). From this she placed the 'Pleistocene-Holocene climatic boundary' at 10200 BP and suggested that there was a general change in climate and a sudden incursion of warm Atlantic water into the Skagerrak-Kattegat at this time.

However, this model contrasts with records from deeper environments in the Skagerrak-Kattegat. Arctic/subarctic assemblages do not disappear before 9600 BP in the well-dated Skagen 3/4 core (Figure 1, palaeo-waterdepth around 100 m; Conradsen and Nielsen, in press) (core GIK 15530–4 from the deep Skagerrak has upper limit of arctic/subarctic foraminiferal assemblages, approximately coinciding with the end of stable $\delta^{18}O$ values, of apparently early Preboreal age, but the chronology of this core is unfortunately somewhat uncertain (Erlenkeuser, 1985; Nagy and Qvale, 1985)). Hence the major temperature change in the deep environments occurred at around 9600 BP. This transition must reflect influx of warm Atlantic water into the area.

The present data therefore contribute to the rather startling picture that emerges for the late Younger Dryas/early Preboreal of the area: while cold deep water conditions occurred in the Skagerrak and possibly the deep Kattegat, warmer low-salinity surface waters prevailed at the same time in the remainder of the Kattegat. During this period, the Skagerrak-Kattegat probably experienced an estuarine circulation pattern. Huge amounts of meltwater were released from the retreating ice sheet at the end of the Younger Dryas, possibly creating strong stratification of the water masses. At present outflowing spring meltwater from the Baltic is warmed up mainly by the atmosphere (Christiansen, pers. comm. 1994). Perhaps late Younger Dryas/early Preboreal atmospheric temperatures were sufficiently high to warm up the low salinity surface water layer. Warmer atmospheric temperatures of this period have been recorded by Björck and Möller (1987) and Lemdahl (1991).

The duration of zone 07:A (Figure 3) is not clearly documented in the present data. Furthermore, the interpretation and duration of zone 07:B is uncertain. The transition from zone 07:A to 07:B might be due to the transition to boreal conditions (decrease of *E. hallandense*) at 9600 BP. If this is so, the Preboreal-Boreal is rather condensed in the core, and the possibility of hiati above zone 07:A cannot be excluded.

9600–8000 BP

Records and interpretation

Preboreal-Boreal sediments, comprising mainly laminated, organic-rich silty clay, were recorded in the closely located PSh-2981 and PSh-2983 cores (Figures 1 and 4). The most complete and well-dated sequence is the one from PSh-2542 (Figure 1) published by Christiansen *et al.* (1993). All of these cores penetrated the same type of sequence and exhibit similar foraminiferal development (zones A–D in all cores). The sediments were initially deposited in boreal, lagoonal environments at the margin of the Kattegat basin (Stabell and Thiede, 1986; see also Nielsen and Konradi, 1990). Subsequently a sea-level rise of probably 20 m occurred due to global eustatic sea-level rise (Fairbanks 1989). This would have generated more saline conditions at the core locations (see Christiansen *et al.*, 1993, for further discussion on the palaeoenvironment).

Discussion

This study presents new data from the area covering the period 9600–8000 BP and provides a discussion of the foraminiferal and palaeoceanographic development. These aspects were not discussed in detail by Christiansen *et al.* (1993), who penetrated the same sequence.

The bottom of the Preboreal/Boreal sequence (equivalent to zone 81:A, Figure 4) containing boreal foraminiferal assemblages was radiocarbon dated to 9600 BP by Christiansen *et al.* (1993). This shows that boreal conditions were fully established in the southern Kattegat immediately after the beginning of influx of warm, Atlantic water into the North Sea-Skagerrak-Kattegat. This influx was from around the north of Great Britain and commenced around 9600 BP (Peacock and Harkness, 1990; Conradsen and Nielsen, in press; see also above).

Foraminiferal zone 81:C (Figure 4) of the sequence, deposited in Boreal times (Christiansen *et al.*, 1993), represents a fairly saline environment. The foraminifer *Nonionellina labradorica* (Dawson), which is an important species for the Holocene stratigraphy of the area (see below), is present in zone 81:C. The zone is very thin in PSh-2981 but is better developed in PSh-2542 (*c.* 70 cm, Christiansen *et al.* 1993) and the undated PSh-2983 (*c.* 60 cm, location marked on Figure 1).

For several reasons, zone C of the sequence was probably not seriously affected by downward bioturbation of younger sediments: first, the thickness of zone C; second, the thin sediment layer of zone D overlying zone C; third, the absolute number of *N. labradorica* per gram sediment is approximately constant in zones C and D in PSh-2542 (Christiansen *et al.*, 1993) and PSh-2983; and, finally, the orderly succession of

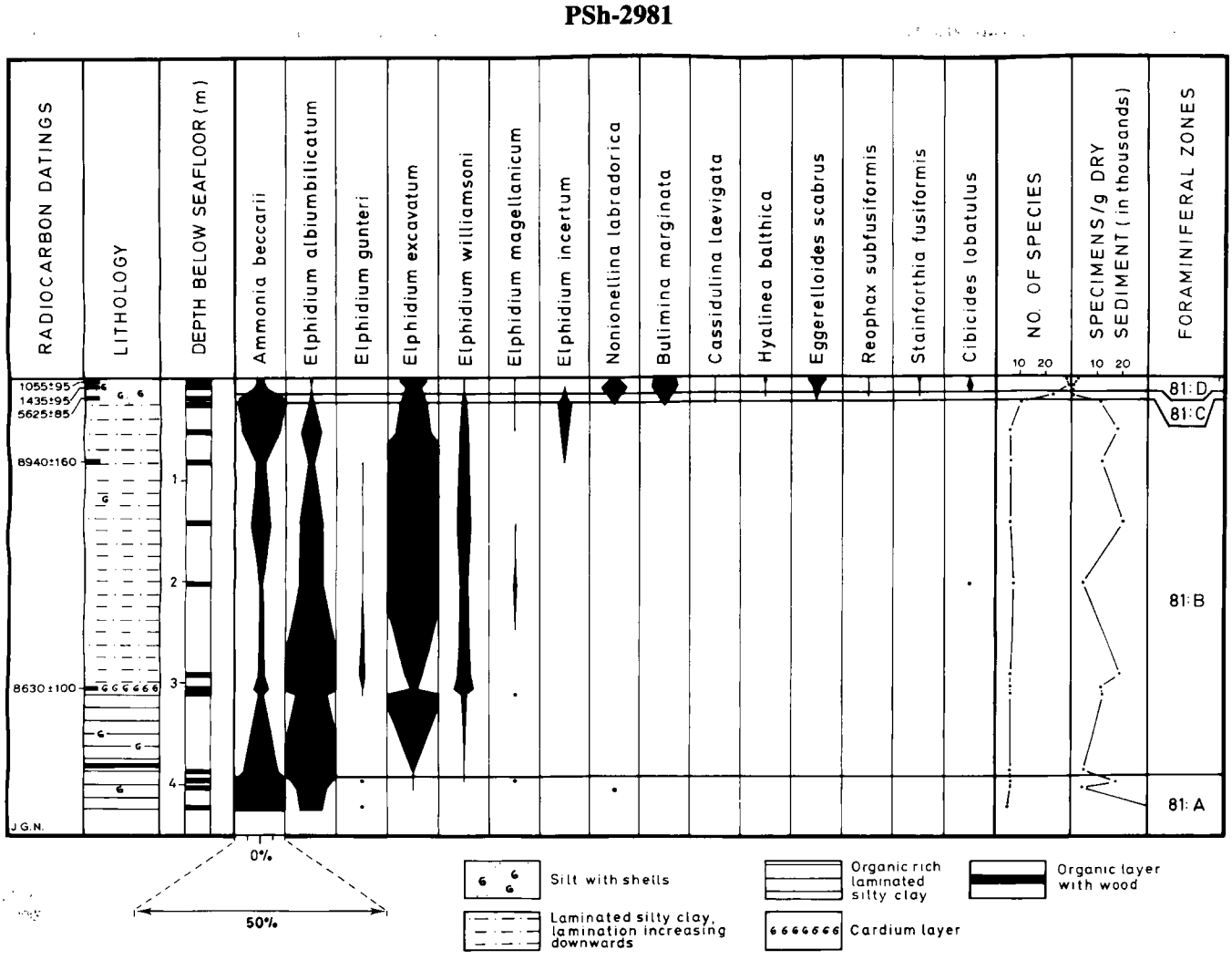

Figure 4 Foraminiferal range chart of selected species in core PSh-2981.

dates in PSh-2542 (Christiansen *et al.*, 1993). This shows that *N. labradorica* was present in the southern Kattegat in early Holocene times, a period when the water masses of the region experienced a slow, gradual warming (interpreted from observations/temperature proxies in, for example, Erlenkeuser, 1985; Nagy and Qvale, 1985; Peacock and Harkness, 1990; Lehman and Keigwin, 1992; Seidenkrantz and Knudsen, 1993; and Conradsen and Nielsen, in press). *N. labradorica* consequently survived in the area until the establishment of the modern circulation pattern around 8000 BP. Less certain observations (uncertain chronologies and/or influence of reworking) of Preboreal-Boreal occurrences of *N. labradorica* in the Kattegat were made by Fält (1982), Knudsen and Nordberg (1987) and Seidenkrantz and Knudsen (1993). The radiocarbon age of 5620 ± 85 BP in zone 81:C in PSh-2981 (Figure 4) is probably erroneous, as this zone is extremly thin in this core and was probably contaminated by bioturbation or during sampling.

The hydrography of the southern Kattegat may have been influenced more by the opening of a connection to the Baltic than the continuing Skagerrak-Kattegat connection. This may explain why PSh-2542, according to the radiocarbon dates (Christiansen *et al.*, 1993), records the major hydrographic change around, or possibly slightly before, 8000 BP (confirmed by Björck, in press, in his review of the history of the Baltic). However, the modern general circulation pattern of the Skagerrak was not fully established until 7600 BP, after the opening of a southern North Sea connection to the Atlantic via the English Channel (Conradsen and Nielsen, in press). This indicates that the modern-like circulation pattern was not established instantaneously over the whole of the Skagerrak-Kattegat region, but occurred at an earlier time in the southern Kattegat (see also Winn *et al.*, 1986).

Post-8000 BP

Records and interpretation

Post-8000 BP sediments consisting of mud are mainly found in PC 10–07, PSh-2978 and K1 (Figures 3, 5 and 6). The foraminiferal assemblages of these sediments were generally very uniform and were very well preserved. No signs of reworked material, neither shallow-water specimens nor pre-Quaternary specimens, were recorded. Hence both the radiocarbon-dated mollusc fragments and foraminiferal shells are considered *in situ*.

K1 (relatively shallow, water depth *c.* 30 m) clearly reflects a post-8000 BP rise in sea level with a transition from a *Elphidium excavatum* (Terquem) to a *Bulimina marginata* d'Orbigny assemblage (zone K1:A-K1:B, Figure 5). This is also recorded in the lowermost part of post-8000 BP sediments in PC 10–07 (zone 07:C-07:D1, Figure 3). Hence, *B. marginata* assemblages became established at all core locations relatively quickly after 8000 BP. This assemblage at present dominates the deeper parts of the Kattegat (below *c.* 25 m; Conradsen, 1993; Conradsen *et al.*, 1994).

The foraminiferal assemblages from the upper part of PSh-

2978 and K1 are increasingly influenced by agglutinated species (*Eggerelloides scabrus* (Williamson), *Spiroplectammina biformis* (Parker and Jones) and *Reophax subfusiformis* Earland) owing to either younger hydrographic changes not considered here or to limited down-core preservation potential (Nordberg and Bergsten, 1988).

Discussion

Nordberg and Bergsten (1988) and Nordberg (1989) established a sedimentological and biostratigraphical model for the Holocene of the southern Kattegat. According to their model, a mid-Holocene major hydrographic change resulted in a shift in deposition centres from shallow areas (< *c.* 25 m) before the change to deeper areas (> *c.* 25 m) after the change. In some of their cores, the change was recorded as resumed sedimentation. Contemporaneous with this change, *N. labradorica* migrated into the southern Kattegat and gradually increased. *N. labradorica* co-occurred with the large, lobulate variety of *Ammonia beccarii* (Linné). Nordberg and Bergsten (1988) and Nordberg (1989) placed the marker level at the first appearance of *N. labradorica* (<0.5% in some cores). The stratigraphic level of the hydrographic change was dated to 4000 BP by pollen stratigraphy, which was supported by one radiocarbon date. Later, Nordberg (1991) extended the interpretation of a major 4000 BP hydrographic change to incorporate the entire Skagerrak-Kattegat.

The distinction between varieties of *A. beccarii* proved difficult in the present material and is consequently not considered. However, the pattern of appearance and gradually increasing frequencies of *N. labradorica* in post-8000 BP sediments is also found in PSh-2978, PC 10–07 and K1 (Figures 4–6; water depth *c.* 30–50 m). The migration of *N. labradorica* was, as demonstrated in the present study, a Holocene reappearance in the area.

It is important to stress that it is the first appearance of *N. labradorica* that marks the hydrographic change. Unfortunately, it may be impossible to date the first appearance of *N. labradorica* exactly in cores from the area, because bioturbation blurs the event and because the exact timing of the first appearance in a process of gradually increasing frequencies is very difficult to determine. These problems are amplified in cores at water depths approaching the upper limit of living *N. labradorica* (*c.* 20 m in the modern Kattegat; Cedhagen, 1991; Conradsen *et al.*, 1994), where the species is rare.

However, frequencies of *N. labradorica* increase gradually over a 2-m-thick sequence in K1 (Figure 5). Furthermore, the presence of a 1-cm-thick, undisturbed silt layer, which may represent a storm layer, in PSh-2978 at a depth of *c.* 1 m is important (Figure 6). This silt layer is *c.* 70 cm above the first appearance level of *N. labradorica* (Figure 6). These features show that the appearance and gradual increase of *N. labradorica* in the present cores is not an artifact of bioturbation. Hence, the first appearance of *N. labradorica*, according to the radiocarbon dates, must have been prior to 5000 BP (Figures 5–6).

The present study adapts the model of Nordberg and Bergsten (1988) and Nordberg (1989; 1991), but redates the migration of *N. labradorica* and hence the change in hydro-

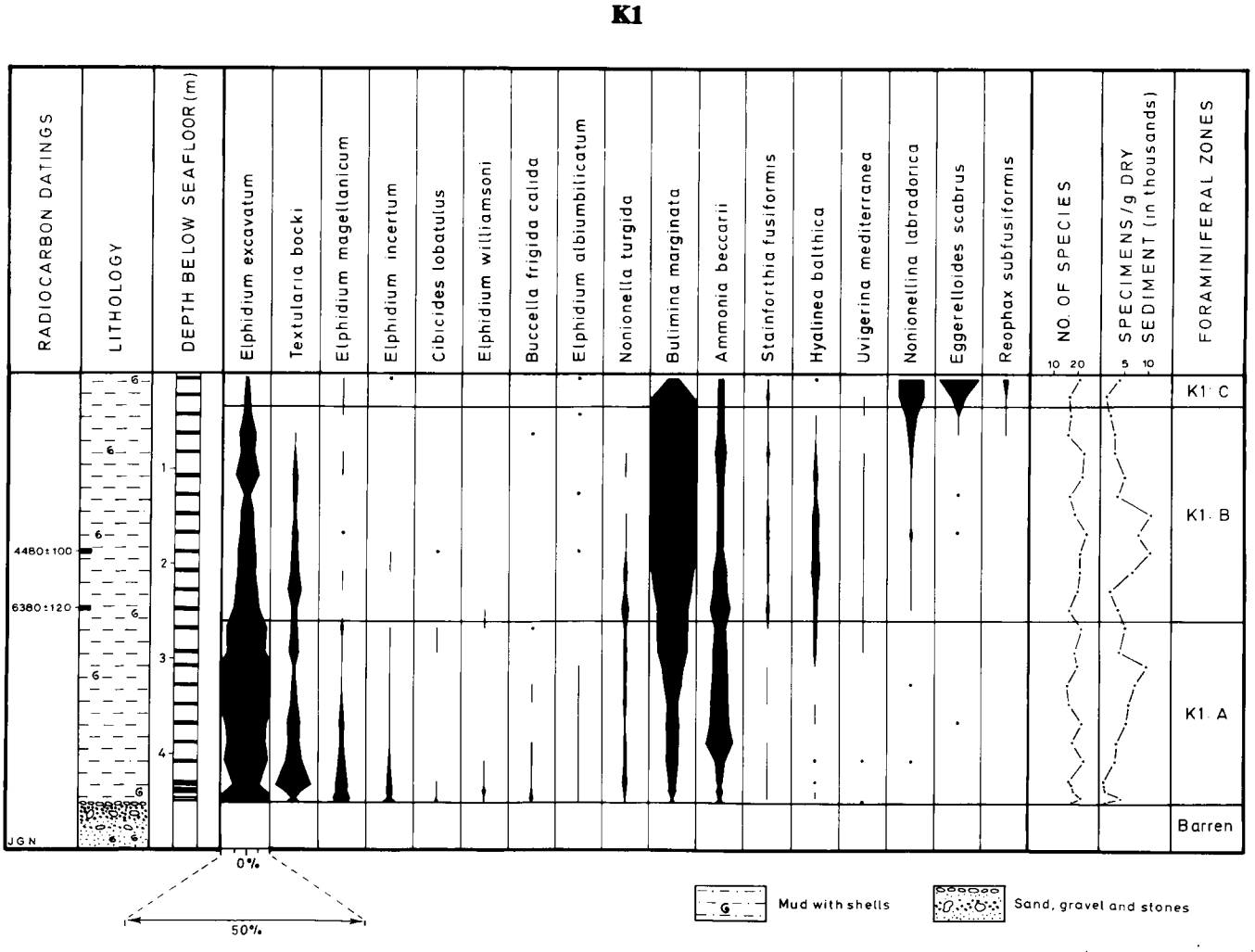

Figure 5 Foraminiferal range chart of selected species in core K1.

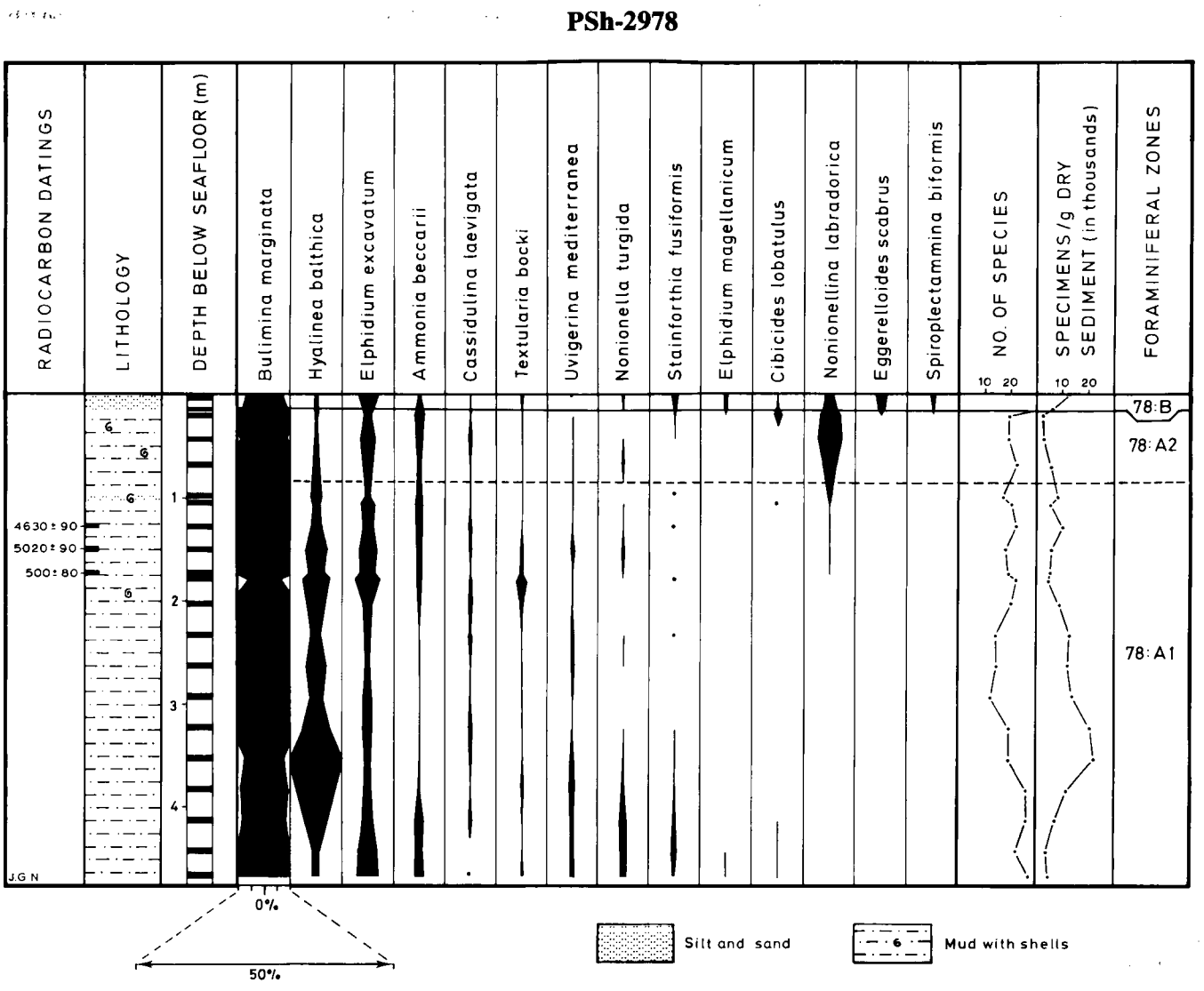

Figure 6 Foraminiferal range chart of selected species in core PSh-2978.

graphy and sedimentation pattern to sometime before 5000 BP. The change consequently occurred around the time of the 5500 BP hydrographic change recorded in the 115 m Holocene record of the Skagen 3/4 core (Figure 1; Conradsen and Nielsen, in press).

The data of the present study therefore extends the interpretation from the Skagen 3/4 core and links it to the work of Nordberg and Bergsten (1988) and Nordberg (1989; 1991). Hence a major hydrographic change affecting the whole Skagerrak-Kattegat is recognized at 5500 BP.

The hydrographic change is interpreted here as a response to the well-known climatic deterioration at the end of the Atlantic chronozone, and it possibly reflects a cooling event affecting the whole North Atlantic region. The local effect of this cooling in the Skagerrak-Kattegat was possibly a strengthening of the Jutland Current, which runs along the west coast of Jutland (Figure 1), and a stronger inflow of saline North Sea water into the Kattegat creating pronounced stratification of the water masses (see Nordberg and Bergsten, 1988; Nordberg, 1991; and Conradsen and Nielsen, in press, for further discussion).

The redating of the hydrographic change does create inconsistencies between the different chronologic tools applied. The pollen-stratigraphic interpretation of Nordberg and Bergsten (1988) and Nordberg (1989; 1991), particularly the interpretation of a *Ulmus* decline below the appearance of *N. labradorica*, yields different results than the radiocarbon dates of the present study. However, there are no obvious reasons to doubt the validity of the dates determining the first appearance of *N. labradorica*. It should also be noted, that the first appearance of *N. labradorica* in the core presented by Nordberg (1991) could very well be placed below the radiocarbon dated level of 4515 ± 95 BP. Moreover, an interpretation of a major hydrographic change in the vicinity of the Kattegat/Skagerrak transition, very precisely dated at 5500 BP in the Skagen 3/4 core (Figure 1; Conradsen and Nielsen, in press), but not recorded in the southern Kattegat, and of a major hydrographic change at 4000 BP in the southern Kattegat (Nordberg and Bergsten, 1988; Nordberg, 1989; 1991), which is not seen in Skagen 3/4, is not very likely.

Conclusions

1. All late Younger Dryas–early Preboreal foraminiferal records from shallow water environments of the Kattegat document relatively warm surface-water conditions. This is in contrast to deep-water environments of the Skagerrak/northern Kattegat, where cold arctic-subarctic water prevailed until 9600 BP.
2. Full interglacial, boreal conditions developed in the southern Kattegat at 9600 BP, as a result of the influx of warm,

North Atlantic water. The area experienced a rise in sea level until 8000 BP. During this period, *N. labradorica* was present in deeper environments of the area.

3. A major hydrographic change, which altered sedimentological and environmental conditions, occurred around 8000 BP, owing to the opening of a connection to the Baltic. This created the modern circulation system in the region. The relative rise in sea level continued for a period after this event.

4. A change in the hydrographic, sedimentological and environmental conditions occurred at 5500 BP. This event, previously dated at 4000 BP, is marked by the reappearance of *N. labradorica* into the southern Kattegat. It probably reflects the climatic cooling at the end of Atlantic times, which caused a strengthening of the Jutland Current and a stronger inflow of saline North Sea water into the Kattegat.

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