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INTERGLACIAL AND GLACIAL CLIMATE OSCILLATIONS IN A MARINE SHELF SEQUENCE FROM NORTHERN DENMARK — A MULTIDISCIPLINARY STUDY

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Abstract—A 22.5 m long marine shelf sequence in northern Denmark covers the climatic shifts from glacial environments, through interglacial and into early glacial conditions. The interglacial was interrupted by two cool intervals. Also the early glacial succession experienced oscillations of the climate, and a period with ameliorated temperature conditions has been separated as an interstadial. These results are based on a multidisciplinary high-resolution study of lithology, foraminifera, ostracods, macrofauna, diatoms and stable isotopes in a silty clay sequence from a borehole at Nørre Lyngby (70.5–48.0 m depth). The lithostratigraphy and the variations in depositional environment in the area is supported by a reflection seismic profile across the core site. The chronostratigraphy is discussed on the basis of biostratigraphical correlation and seismostratigraphy as well as Optically Stimulated Luminescence (OSL) dating and amino acid measurements. The biostratigraphy and the OSL dates suggest an Eemian age for the interglacial, while amino acid results point to an older age. If the interglacial is confirmed as Eemian, we believe that the succeeding interstadial period is likely to be correlated with the Brørup Interstadial. The climatic changes in this eastern part of the North Sea region are closely linked with changes in the North Atlantic circulation pattern, and the environmental fluctuations at Nørre Lyngby are therefore believed to reflect fluctuations in the past regional climatic and oceanic system. © 1998 Published by Elsevier Science Ltd. All rights reserved.

INTRODUCTION

The study of marine glacial and interglacial deposits of Eemian or pre-Eemian age often suffers from the lack of suitable high-resolution records and from difficulties associated with obtaining age control.

The purpose of this paper is to present a high-resolution study of a marine glacial-interglacial-glacial sediment sequence in a core from Nørre Lyngby (Fig. 1), northern Denmark, based on foraminiferal, ostracodal, macrofaunal and diatom assemblages as well as stable isotope evidence. The architecture of the succession is illustrated by a high-resolution reflection seismic profile across the site, and the chronology is discussed on the basis of the combined results of biostratigraphical correlations, Optically Stimulated Luminescence (OSL) dating as well as amino acid ratios (Hans Petter Sejrup, pers. commun., 1996).

The study is focused on the marine environments and climatic changes from a late glacial period through an entire interglacial and into early glacial conditions. This interglacial has previously been assigned to the Eemian (Lykke-Andersen, 1987; Seidenkrantz *et al.*, 1995). However, some contradictory results have turned up in connection with the absolute dating of the interglacial.

REGIONAL SETTING

The Nørre Lyngby core site is located on the south-western margin of an up to 300 m deep Quaternary marine embayment, the Kattegat depression, trending from the northwest to the southeast across northern Denmark and into the Kattegat (Lykke-Andersen *et al.*, 1993). During the Late Quaternary this basin was gradually filled with mainly marine sediments. The level of the pre-Quaternary surface in the area is shown in Fig. 2.

The present North Sea and Skagerrak waters originate from the North Atlantic surface water entering mainly as currents north of Scotland (ca. 90%) but also through the English Channel (ca. 9%) (Otto, 1976) (Fig. 1). The circulation pattern in the North Atlantic and in the Greenland–Iceland–Norwegian Seas plays an important role for the understanding of past global and regional climatic and oceanographic systems (e.g., Berger *et al.*, 1987; Berger, 1990; Lehman and Keigwin, 1992; Imbrie *et al.*, 1992, 1993; Weaver and Hughes, 1994). The close link to the North Atlantic current system makes the North Sea a well-suited area for palaeoclimate studies. Furthermore, shelf sediments provide better temporal resolution than most deep sea sediments because of a generally higher accumulation rate in such areas.

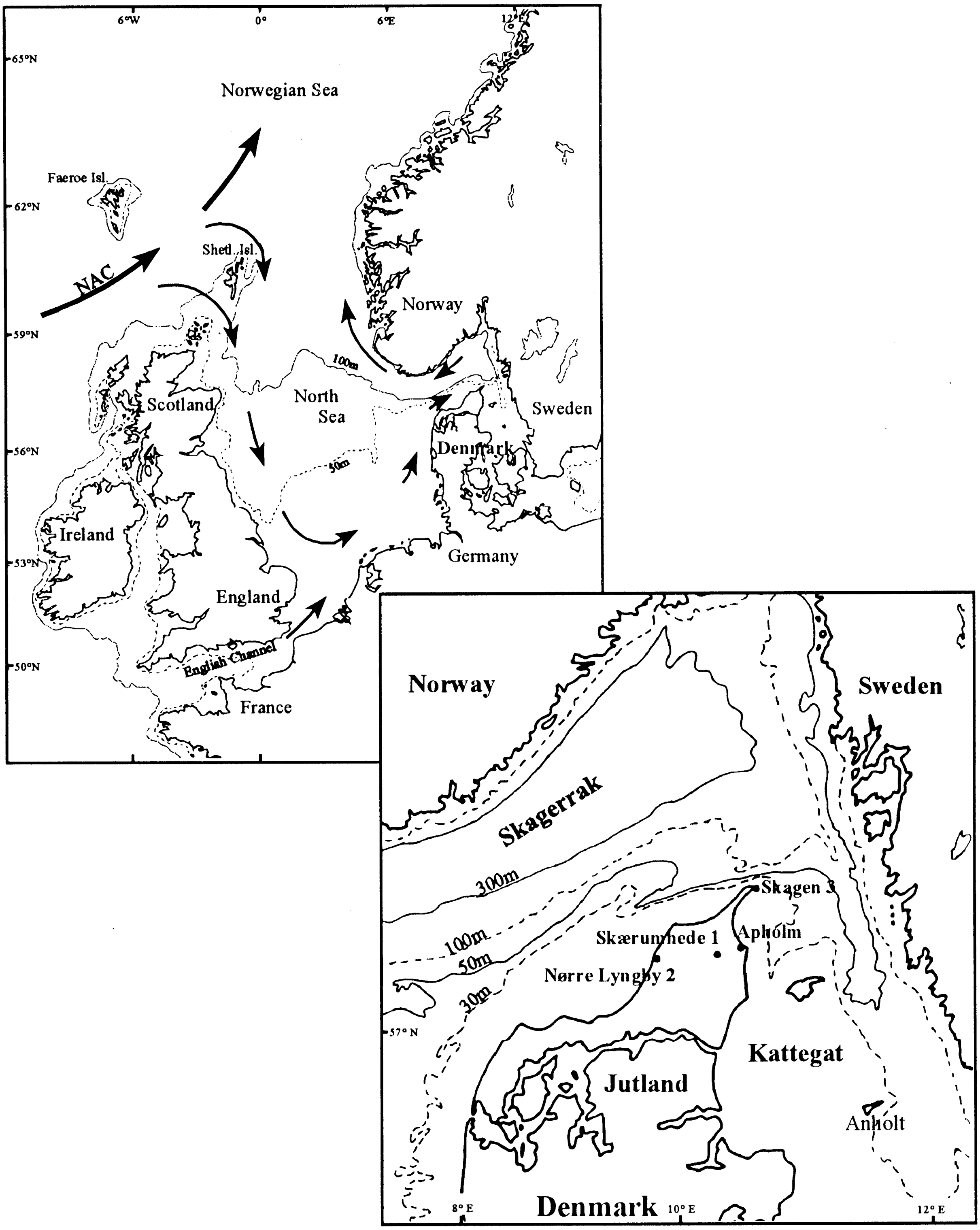

FIG. 1. Location maps showing the sites mentioned in the text as well as the present surface circulation pattern in the North Sea. NAC = North Atlantic Current.

MATERIAL AND METHODS

The Nørre Lyngby 2 core site is located on the beach near the village of Nørre Lyngby at the west coast of Jutland (Fig. 1). The 70.5 m deep borehole was drilled in 1993 using rotary drilling equipment obtaining core sections of 1.5 m length and a diameter of 11 cm. Each core section was split into halves, and the sediments were described, photographed and sampled.

Samples for grain size analysis were extracted from the entire core, while dense sampling for foraminiferal, ostracodal, macrofaunal and diatom analyses was concentrated in the interval between 48.0 and 70.5 m depth where core material was obtained with 100% recovery.

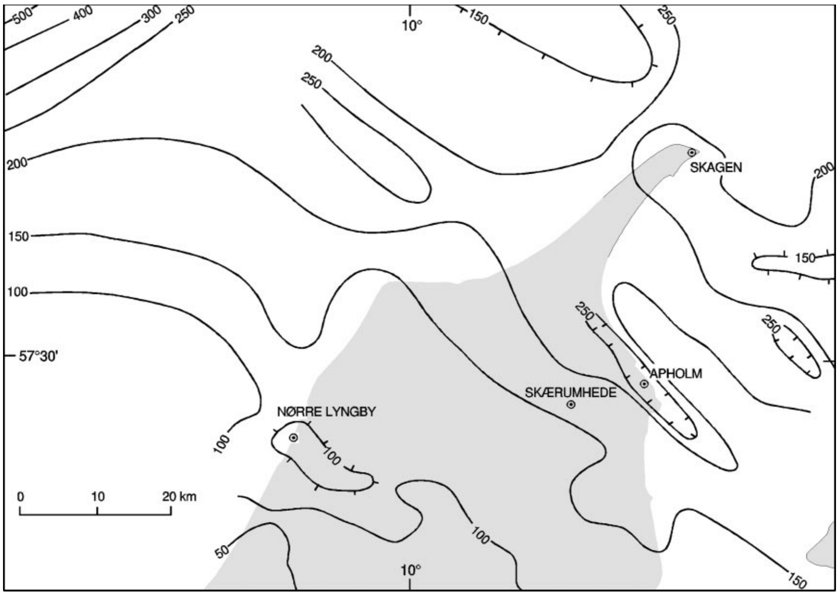

FIG. 2. The level of the pre-Quaternary surface in northern Jutland (Lower Cretaceous sands and Upper Cretaceous chalk). The core sites mentioned in the text are indicated on the map.

Two to three cm thick sample slices were taken from one-half of the core, and the outer layer of ca. 1 cm 'core bark' was removed from each sample in order to prevent downcore contamination.

Seismics and Lithology

A 235 m long reflection seismic profile was recorded along the beach in order to obtain a detailed image of the Quaternary sedimentary sequence at the core site and in the vicinity of the site. The location of the core site in relation to the seismic profile is shown in Fig. 3. The field set-up with geophone spacing 2 m, shot spacing 4 m and charge size 2g (dynamite), and the processing with bandpass filter 200–1440 Hz were designed to produce an optimal resolution in the seismic profile. It is estimated that the vertical and the horizontal resolutions are in the order of 1 m and 5 m, respectively. In order to obtain a precise correlation between the two way travel times, as given on the vertical axis of the seismic profile (Fig. 3), and the depths measured in the borehole, travel times were measured directly by means of a hydrophone lowered into the drill hole. The relation between depths and two way travel times is illustrated in Fig. 4.

The sedimentary sequence encountered in the Nørre Lyngby 2 core ranges from silty clay to silty sand. On the basis of the visual core descriptions and on grain size analysis (carried out at the Technical University of Denmark using a Sedigraph 5100) the sequence can be subdivided into four main lithological units (Units a–d, Fig. 4).

Unit a (70.5–48.0 m depth) consists of relatively homogeneous clay-silt mixtures with sand as a minor component. A few cobbles were encountered at two discrete levels (48.0 and 58.5 m). A slight upwards coarsening is expressed by the clay content decreasing from 60% at the base to about 40% at the top and a complementary increase in sand content from $< 5\%$ to about 20%. The water content in the sediments of unit a is remarkably high, i.e., 25–31% (mean 28%, 7 samples) in the lower part (61–70 m) and 17–27% (mean 24%, 8 samples) in the upper part (48–61 m)(Knutz, 1994). In *unit b* (48–27 m) the core recovery was very poor. In addition to a few short core sections containing silty sand in the central part of the unit, only few samples were obtained from the core catcher. On the basis of these few samples the unit is considered to be mainly composed of silty and clayey sand with an upwards fining trend. The analyses show that the sand contents decrease from the base to the top from about 80 to 40–50%. *Unit c* (27–18 m) is composed of silty clay grading upwards to sand-silt-clay mixtures. The sand content increases upwards from 5% at the base to 40–50% at the top. *Unit d* (18–0 m depth) consists of laminated, relatively homogeneous silty clay with a clay content varying between 30 and 50% and with a slight upwards coarsening tendency in the two intervals, i.e., 18–8 m and 8–0 m, respectively. An AMS ^{14}C dating (AAR-2742, mixed benthic foraminiferal fauna) from unit d (14.70–14.77 m) gave a maximum age of 15,270 BP (with reservoir correction of 400 yr).

Foraminifera and Ostracods

The sediment samples for foraminiferal and ostracod analysis were processed in accordance with Feyling-Hanssen *et al.* (1971) and Meldgaard and Knudsen (1979). This includes wet sieving with mesh sizes of 0.063, 0.1 and 1.0 mm. The foraminifera in the 0.1–1.0 mm size fractions were subsequently concentrated in CCl_4 ($\rho = 1.59\ g\,cm^{-3}$). At least 300 specimens of benthic foraminifera were identified and

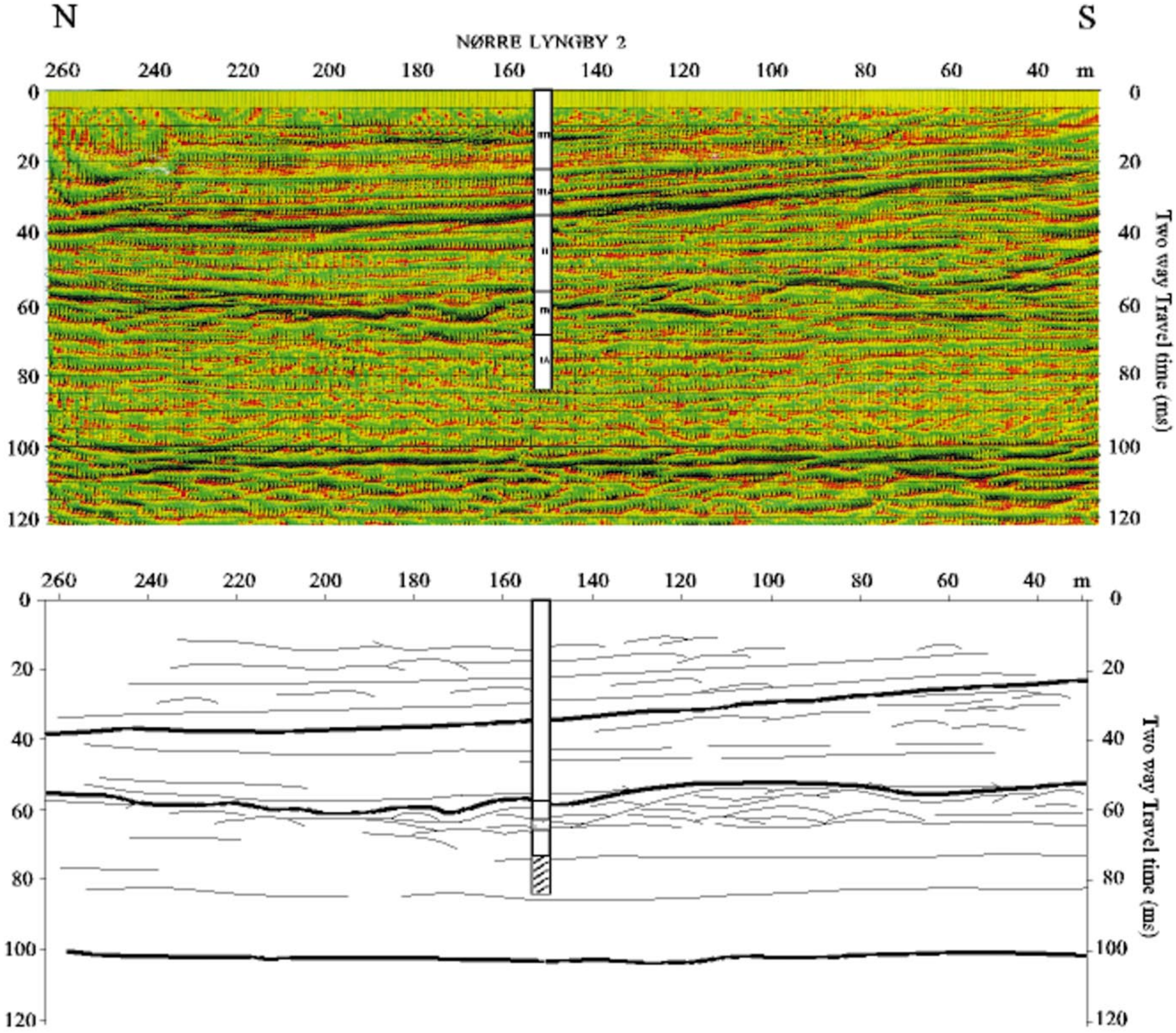

FIG. 3. Reflection seismic profile (235 m) along the beach at the core site Nørre Lyngby 2. Horizontal scale in meters. Vertical scale two way travel time in milliseconds (ms). No vertical exaggeration. Seismic stratigraphic units (I–III) are indicated at the core site. Arrows indicate onlaps and apparent truncation. The stratigraphic units described in the text correspond to the seismic subunits IA and IB. Location of the interglacial and the interstadial intervals are indicated by cross hatching and dot signature, respectively. Depth scale is shown on Fig. 4.

counted from the light fractions of each sample, and the total number of planktonic foraminifera was also registered (Figs. 5–9, Table 1).

The benthic foraminiferal species have been divided into three 'climatic tolerance' groups (the arctic, the indifferent and transitional, and the boreal (temperate) group (Table 1, Figs. 7 and 8) according to their present distribution in the eastern North Atlantic area. The 'boreal' group also includes lusitanian (warm temperate) species, and the 'arctic' group includes subarctic species. The 'indifferent and transitional' group contains species which may be found both in cold boreal and subarctic assemblages as well as cosmopolitan species and species with uncertain environmental preference. Also *Elphidium excavatum* is included in this group as it has not been separated in its arctic form *clavata* Cushman and boreal form *selseyensis* (Heron-Allen and Earland). The ecological interpretation of the benthic foraminifera is based on Nørvang (1945), Jarke (1961), Nagy (1965), Gudina and Evzerov (1973), Sejrup *et al.* (1981), Feyling-Hanssen (1983), Murray (1991), Conradsen *et al.* (1994), Hald *et al.* (1994), Steinsund (1994), Kristensen and Sejrup (1996) and Hald and Korsun (1997).

The ostracods were picked from the heavy 0.1–1.0 mm fraction, and at least 300 valves were identified and counted when possible (Figs. 5 and 6, Table 2). The environmental interpretations are generally based on Sars (1928), Elofson (1941), Athersuch *et al.* (1989) and Penney (1993).

Macrofaunas

All the residues (129 samples, > 63 μm) from the foraminiferal samples were examined for macrofauna.

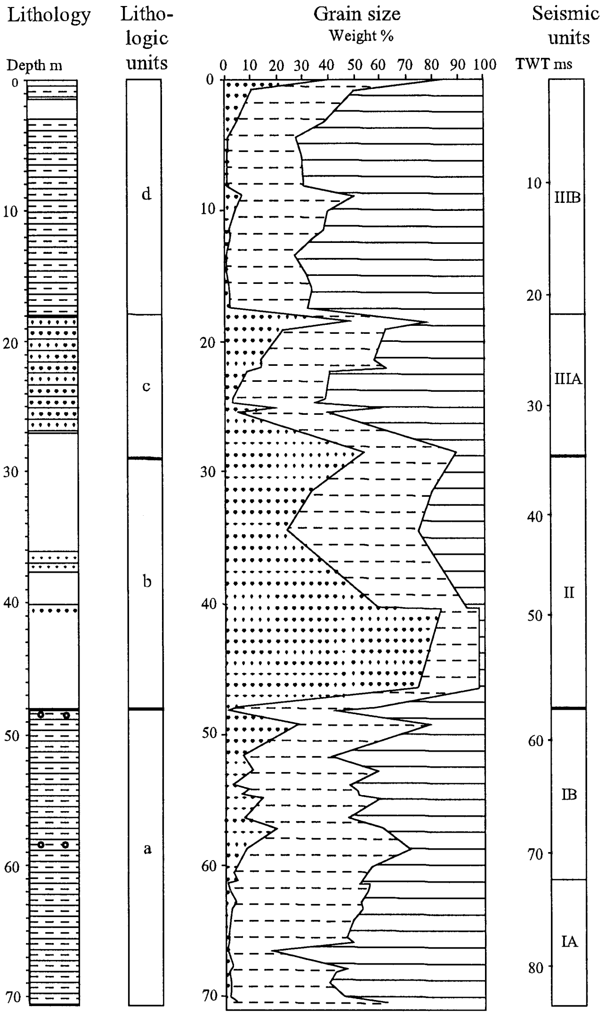

FIG. 4. Lithological composition and seismic units of the sequence in the Nørre Lyngby 2 core. Horizontal hatching = clay; horizontal dotted line hatching = silt; dotted signature = sand; circles = cobbles; white intervals = no recovery. The vertical scale at the column with seismic units shows two way travel times (TWT) in milliseconds (ms) calculated from borehole measurements.

An additional 91 subsamples from the same interval were processed (freeze-dried, disaggregated in very dilute hydrogen peroxide) and the residues greater than 63 µm examined for macrofauna. The sample sizes were small, particularly when compared with those in the classic Skærumhede I borehole (Jessen et al., 1910), and the macrofauna is thus almost certainly under-represented. In the following account the nomenclature broadly follows that of Smith and Heppell (1991) for the boreal mollusca, Macpherson (1971) for arctic gastropods and Warén (1989a) for protobranch bivalves. The species are listed in Table 3 and the distribution in the Nørre Lyngby 2 core is shown on Fig. 10.

Diatoms

A total of 26 samples from the depth interval 70.44–59.74 m were prepared for diatom analyses. The spread of samples studied was dependent on the sampling pattern established for the foraminiferal work. Standard preparation procedures were used (Battarbee, 1986), these involved digestion of the organics with hydrogen peroxide (H_2O_2 30%) and the removal of the clay/silt fraction by differential centrifuging. The samples were mounted on microscope slides using Naphrax, a resin with a high reflective index. Identification of species was made with reference to standard diatom floras for northwest European waters (Hendey, 1964; Van der Werff and Huls, 1957–1974; Krammer and Lange-Bertalot, 1986–1991; Cleve-Euler, 1951–1955; Hustedt, 1927–1966). All of the samples contained diatoms though the concentration was found to be low. A minimum of 200 diatom valves were counted at each level, and the species were categorised according to salinity tolerances and preferred habitat-lifeform (de Wolf, 1982; Vos and de Wolf, 1988, 1993; Denys, 1991a, b) (Fig. 11A and Fig. 11B). The planktonic and tychoplanktonic species were grouped together as were all benthic forms except epiphytes and aerophilous lifeforms (Fig. 11A). This was done for ease of illustration, and reference is made to specific benthic lifeforms where necessary. The most common diatom species are listed in Table 4.

Stable Isotopes

Oxygen and carbon isotope measurements were performed at the Stable Isotope Laboratory, Bergen, Norway, as described by Jansen et al. (1988) using a Finnigan MAT 251 mass spectrometer. The stable isotope measurements were made on the benthic foraminiferal species *E. excavatum* in the glacial deposits and on *Cassidulina laevigata* in the interglacial sediments (Fig. 12). The values have not been corrected for isotopic disequilibrium effects. Results are given relative to the PDB-standard.

Optically Stimulated Luminescence (OSL) Dating

The OSL measurements (Table 5) were carried out at The Nordic Laboratory for Luminescence Dating, Risø, Denmark, using optically stimulated luminiscence (OSL). Almost all dates are based on the added-dose technique (Aitken, 1992, 1994; Wintle, 1994) using K-feldspar grains (0.1–0.3 mm). However, the result of sample R-964803 (Table 5) is calculated as a mean of the results from the added-dose technique on K-feldspar (47.2 ± 5 ky) and the SARA-method (Mejdahl and Bøtter-Jensen, 1994) on quartz (44.6 ± 5 ky). All dates have been corrected for the shallow trap effect (Mejdahl et al., 1992).

STRATIGRAPHICAL RESULTS AND PALAEOENVIRONMENTS

Seismic Results

The seismic stratigraphic analysis presented here covers the seismic profile down to two way travel times

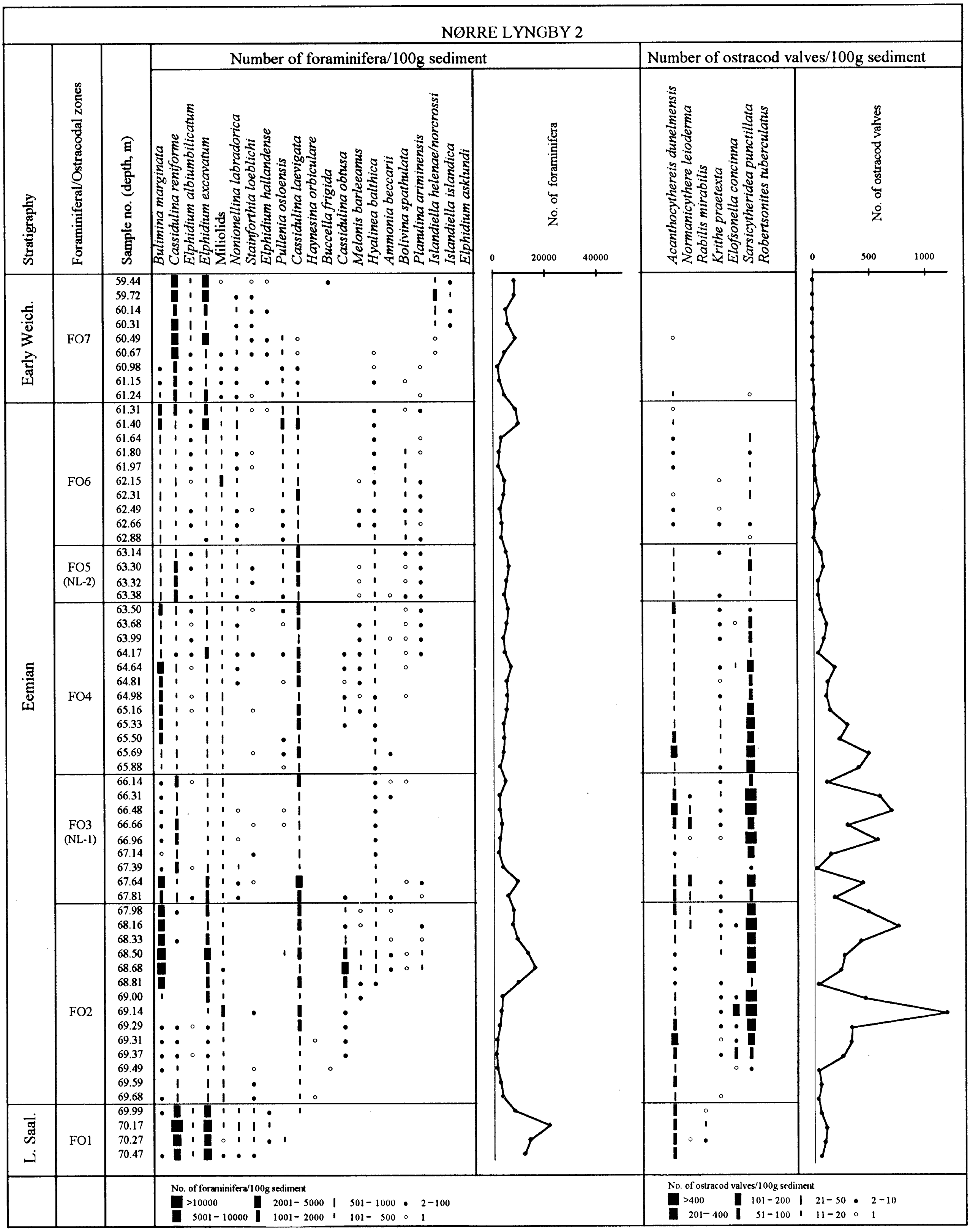

FIG. 5. Concentrations (number per 100 g sediment) of selected benthic foraminiferal species and ostracods in the interglacial deposits (69.90–61.28 m) of the Nørre Lyngby 2 core, including the transition from late glacial conditions below and the succeeding transition to early glacial environments above. The foraminiferal/ostracodal zones (FO1–FO7) are indicated to the left. NL–1 and NL–2 indicate two cool intervals in the interglacial.

(83 ms) corresponding to the total depth of the borehole (70.5 m). Three main seismic units (I–III, Figs. 3 and 4) can be identified at the core site, and each of the units I and III are subdivided into two subunits.

According to the seismic profile the lower boundary of *unit I* is located at a horizontal, high-amplitude reflection at 100 ms (ca. 85 m depth). The unit is divided into an upper *subunit* (*IB*) containing patchy reflections

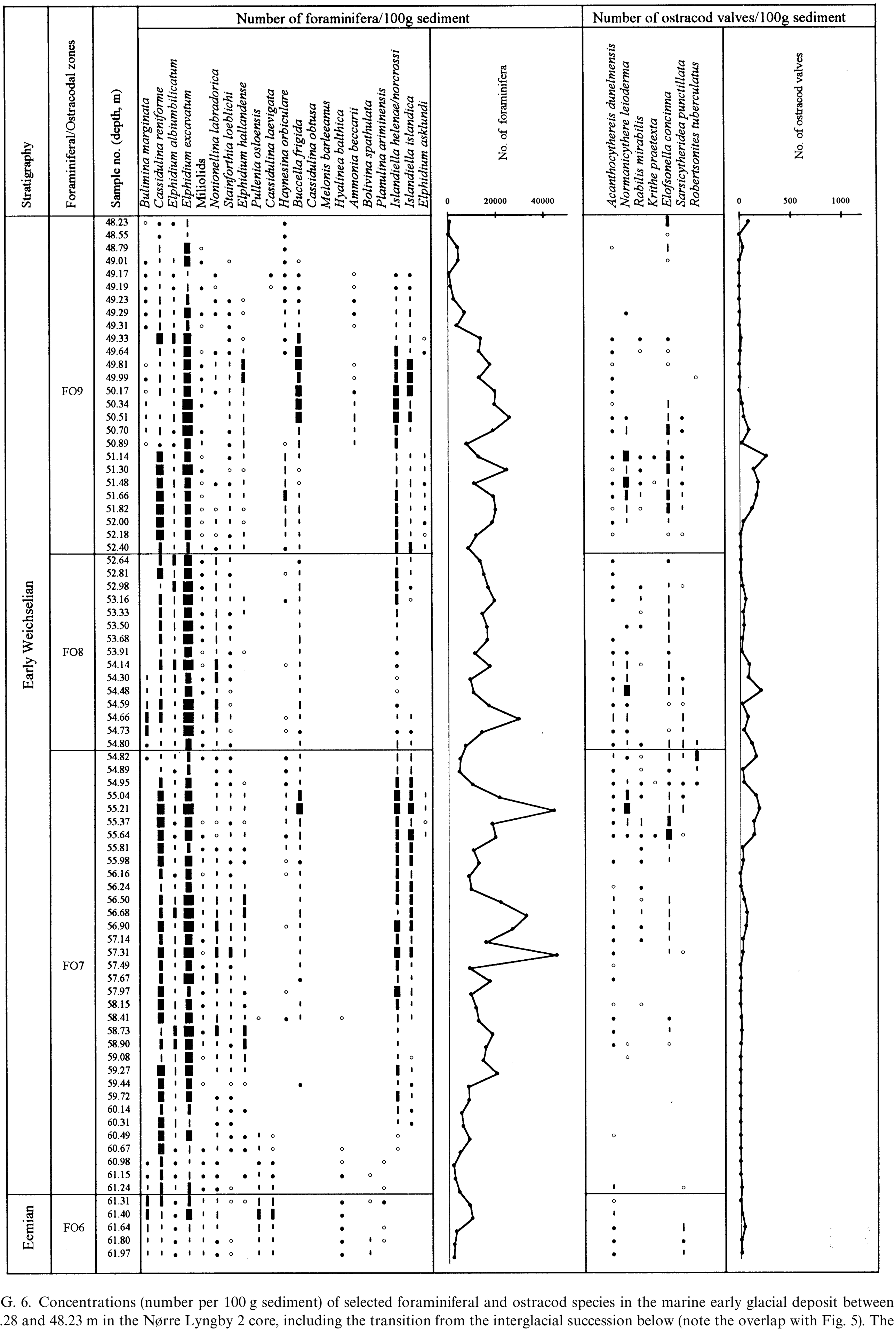

FIG. 6. Concentrations (number per 100 g sediment) of selected foraminiferal and ostracod species in the marine early glacial deposit between 61.28 and 48.23 m in the Nørre Lyngby 2 core, including the transition from the interglacial succession below (note the overlap with Fig. 5). The foraminiferal/ostracodal zones (FO6–FO9) are indicated to the left.

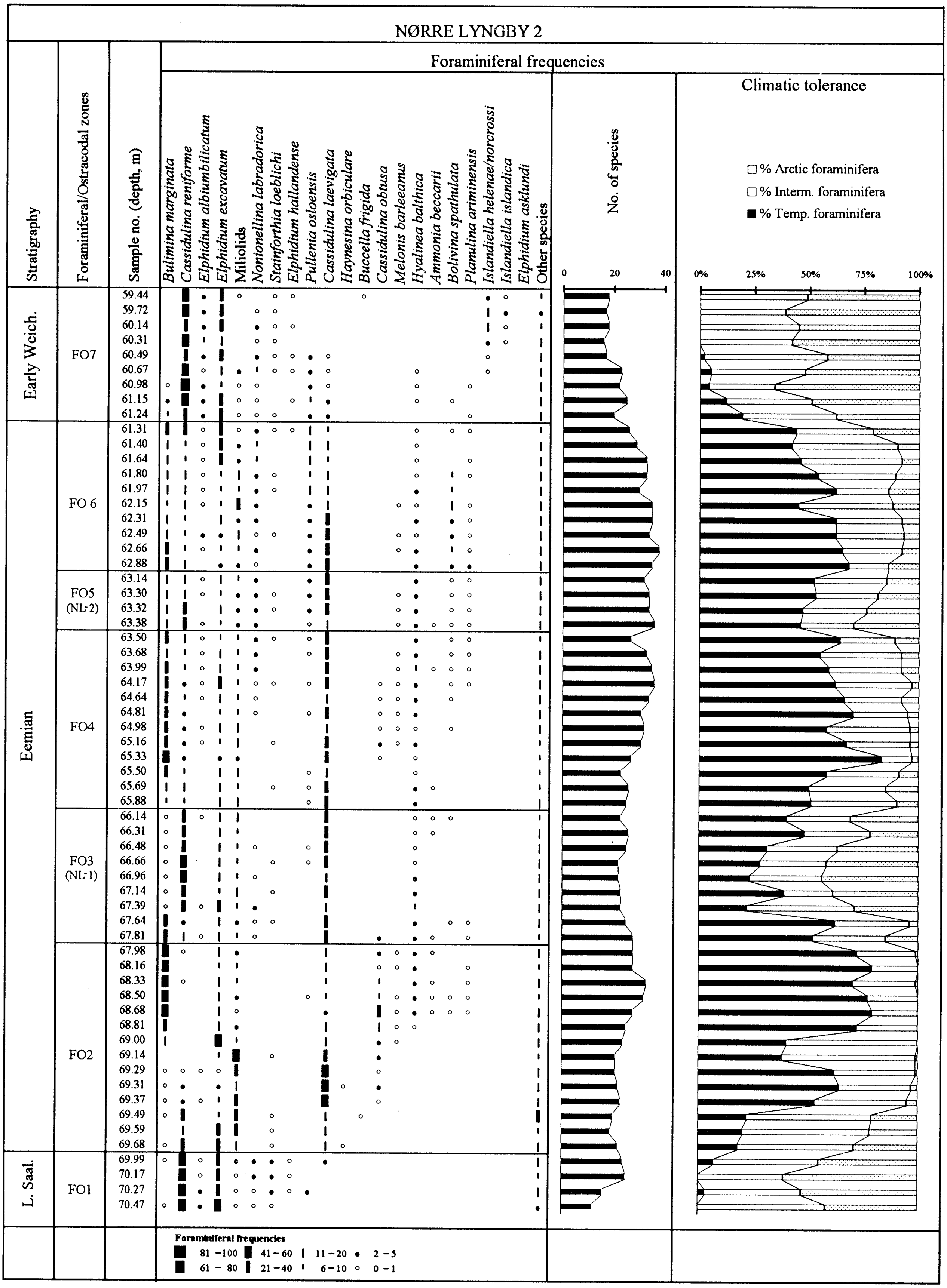

FIG. 7. Percentages of selected foraminiferal species in the interglacial deposits (69.90–61.28 m) in the Nørre Lyngby 2 core, including the transition from late glacial conditions below and the succeeding transition to early glacial environments above. 'Climatic tolerance' illustrates the environmental preference of the benthic foraminifera (Table 1). The foraminiferal/ostracodal zones (FO1–FO7) are indicated to the left. NL–1 and NL–2 indicate two cool intervals in the interglacial.

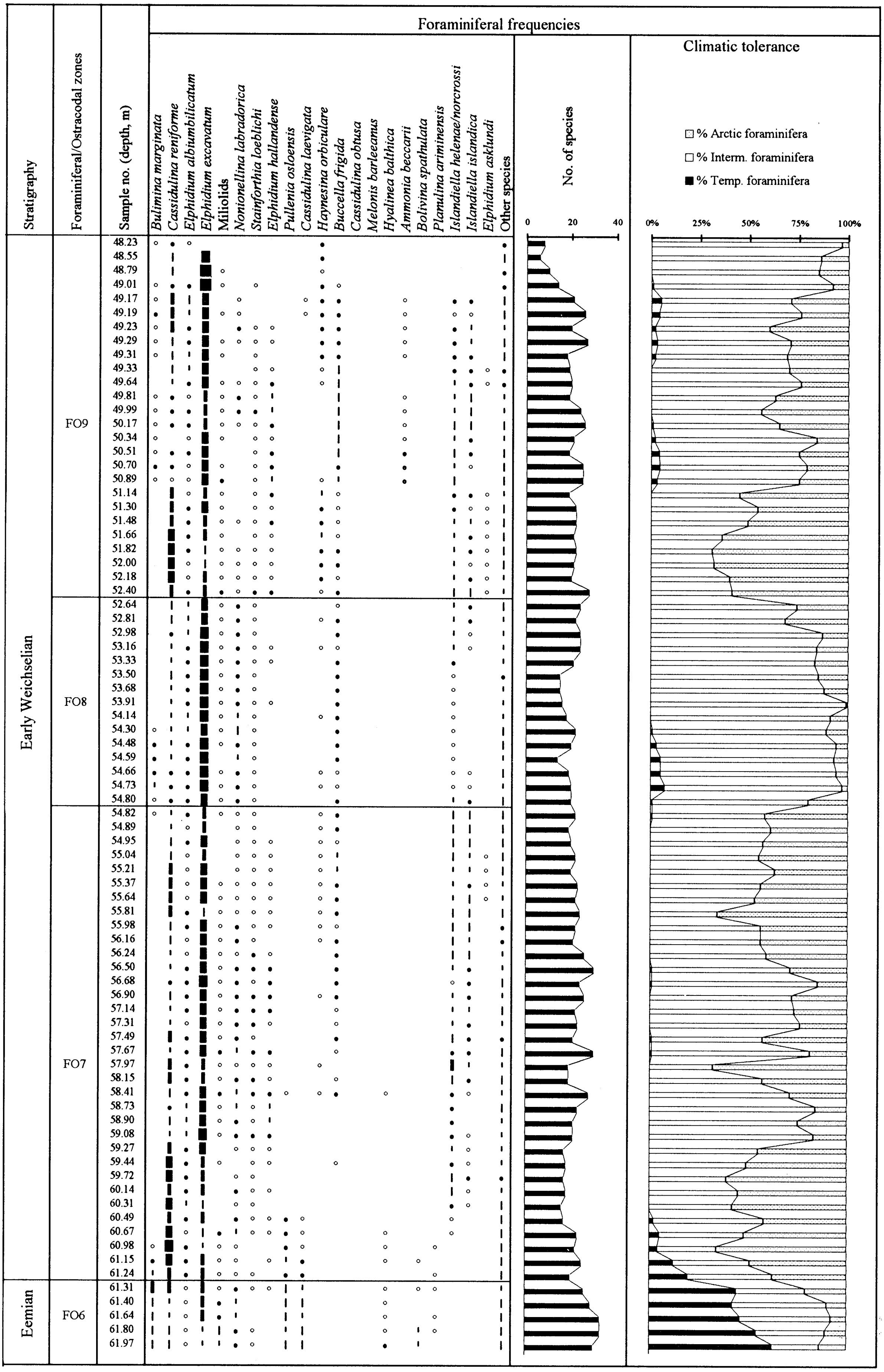

FIG. 8. Percentages of selected foraminiferal species in the marine early glacial deposit between 61.28 and 48.23 m in the Nørre Lyngby 2 core, including the transition from the interglacial succession below (note the overlap with Fig. 7). 'Climatic tolerance' illustrates the environmental preference of the benthic foraminifera (Table 1). The foraminiferal/ostracodal zones (FO6–FO9) are indicated to the left.

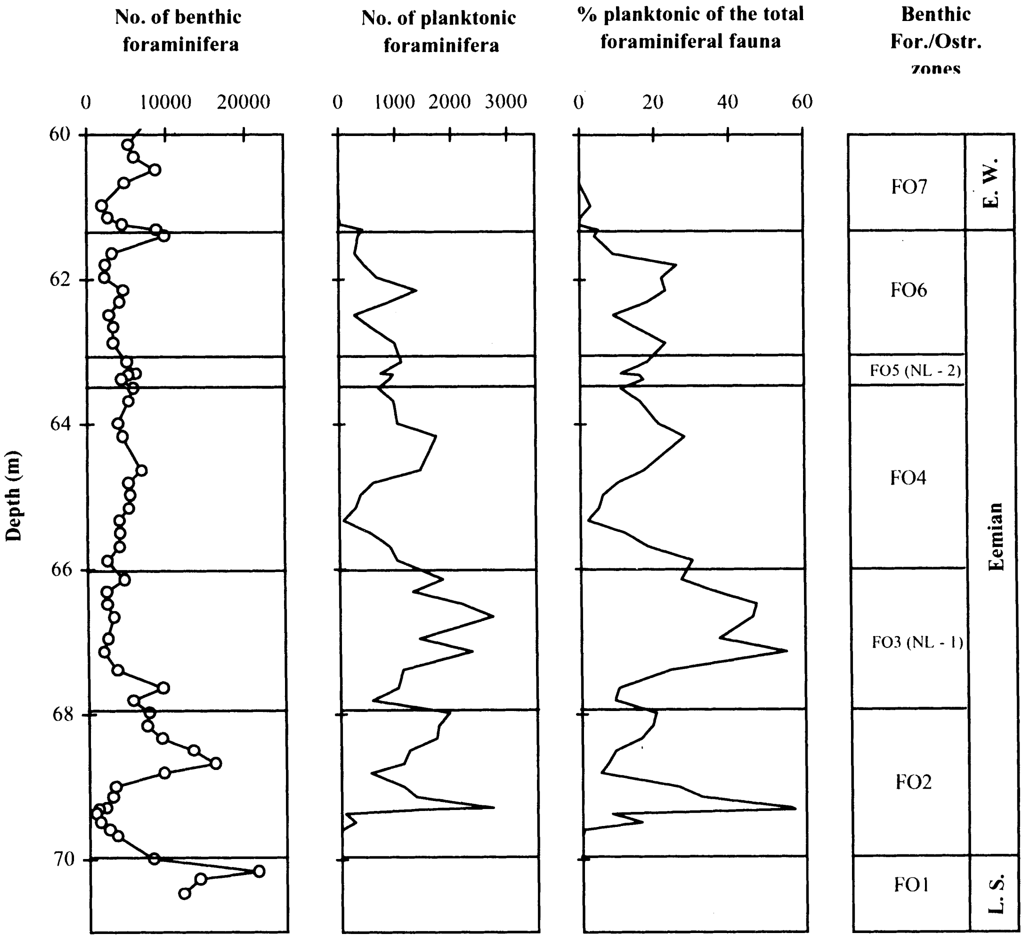

FIG. 9. Total concentrations of benthic and planktonic foraminifera and percentage of planktonic specimens (of total foraminiferal fauna) in the interglacial deposits (69.90–61.28 m; Zones FO2–FO6) of the Nørre Lyngby 2 core, including the transition from late glacial conditions below (Zone FO1) and the succeeding transition to early glacial environments above (Zone FO7). NL–1 and NL–2 indicate two cool intervals in the interglacial.

with strongly variable amplitudes and a lower *subunit* (*IA*) that is almost devoid of reflections. The horizontal boundary between the two subunits is located at a near-horizontal reflection with very low amplitude at ca. 72 ms (61 m). A parallel reflection with very low amplitude is discernible at ca. 85 ms (ca. 72 m). The internal reflections in the upper subunit (IB) form stacks of shallow banks. The surface of this compound bank structure makes up the undulating base of unit II.

Internally *unit II* is characterised by low-amplitude reflections. A few near-horizontal reflections can be traced over substantial parts of the profile. At the base of unit II these reflections onlap the flanks of the banks. South of the borehole, where the thickness of the unit has increased, the internal reflection pattern forms a system of shallow banks in the upper part of the unit. No indications of erosional truncation are seen at the base of unit III.

The base of *unit III* is defined by a high-amplitude reflection that is easily followed through the profile as a surface descending from south to north from ca. 20 ms (16 m) to ca. 40 ms (33 m). South of the core site the base is dipping about 6° northwards, and north of the core site it becomes gradually almost horizontal. Although the appearance of the upper part of the unit may be affected by artefacts produced by the processing, the unit is clearly composed of a lower *subunit* (*IIIA*) with continuous reflections with only minor amplitude variations and an upper *subunit* (*IIIB*) characterised by non-continuous reflections with varying amplitudes. The reflections in the upper subunit indicate the presence of broad, flat banks whereas the internal reflections in the lower subunit show a simple structure with northwards slightly diverging reflections subparallel to the base of the unit. It is noted that the upper part of the subunit IIIA shows indications of shallow bank structures.

The seismic stratigraphic subdivision is strictly compatible with the subdivision based on lithological characters (Fig. 4). The high-amplitude reflections found at the base and top of seismic unit II at two way travel times of 58 and 35 ms correlate with the base and top of the lithostratigraphic unit b at the depths 48 and 29 m. The continuous reflection with relatively high amplitude found at the boundary IIIA/IIIB at 22 ms corresponds with the boundary c/d at 18 m depth. Each of these reflections are generated in zones with

TABLE 1. Foraminifera in the Nørre Lyngby 2 core

Benthic foraminifera

Benthic foraminifera species accounting for more than 1% of the fauna in at least one sample in the Nørre Lyngby 2 core. Species included in the boreal 'climatic tolerance' group of Figs. 7 and 8 are marked with a 'B' (temperate and warm temperate), and those included in the arctic group are marked with an 'A'. All others are left in the 'indifferent and transitional' group.

Ammonia beccarii (Linné, 1758) - B
Astrononion gallowayi Loeblich and Tappan, 1953
Bolivina spathulata (Williamson, 1858) - B
Buccella frigida (Cushman, 1922) - A
Buccella tenerrima (Bandy, 1950)
Bulimina marginata d'Orbigny, 1826 - B
Cassidulina laevigata d'Orbigny, 1826 - B
Cassidulina obtusa Williamson, 1858 - B
Cassidulina reniforme Nørvang, 1945 - A
Cibicides lobatulus (Walker and Jacob, 1798)
Elphidium albiumbilicatum (Weiss, 1954)
Elphidium asklundi Brotzen, 1943 - A
Elphidium bartletti Cushman, 1933 - A
Elphidium excavatum s.l. (Terquem, 1875)
Elphidium hallandense Brotzen, 1943 - A
Elphidium magellanicum Heron-Allen and Earland, 1932
Elphidium margaritaceum Cushman, 1930 - B
Epistominella spp.
Fissurina spp.
Glandulina laevigata d'Orbigny, 1826
Globobulimina turgida (Bailey, 1851) - B
Haynesina orbiculare (Brady, 1881) - A
Hyalinea balthica (Schroeter, 1783) - B
Islandiella helenae Feyling-Hanssen and Buzas, 1976 - A
Islandiella islandica (Nørvang, 1945) - A
Islandiella norcrossi (Cushman, 1933) - A
Lagena spp.
Melonis barleeanus (Williamson, 1858) - B
Miliolinella cf. *enoplostoma* (Reuss, 1851)
Miliolinella subrotunda (Montagu, 1803)
Nonionella iridea Heron-Allen and Earland, 1932 - B
Nonionella turgida (Williamson, 1858)
Nonionellina labradorica (Dawson, 1860)
Oolina spp.
Parafissurina spp.
Planulina ariminensis d'Orbigny, 1826 - B
Polymorphinidae, indeterminata
Pullenia osloensis Feyling-Hanssen, 1954 - B
Pullenia subcarinata (d'Orbigny, 1839)
Pyrgo williamsoni (Silvestri, 1923)
Quinqueloculina agglutinata Cushman, 1917
Quinqueloaculina padana Perconig, 1954 - B
Quinqueloculina seminulum (Linné, 1758)
Quinqueloculina stalkeri Loeblich and Tappan, 1953
Sagrina subspinescens (Cusman, 1922) - B
Sigmoilopsis schlumbergeri (Silvestri, 1904) - B
Sigmoilopsis tenuis (Czjzek, 1848) - B
Stainforthia fusiformis (Williamson, 1858) - B
Stainforthia loeblichi (Feyling-Hanssen, 1954) - A
Textularia truncata Höglund, 1947 - B
Trifarina angulosa (Williamson, 1858) - B
Trifarina fluens (Todd, 1947) - A

Planktonic foraminifera
Globigerina bulloides d'Orbigny, 1826
Neogloboquadrina pachyderma (Ehrenberg, 1861)
Turborotalita quinqueloba (Natland, 1938)

TABLE 2. Ostracods in the Nørre Lyngby 2 core

Acanthocythereis dunelmensis (Norman, 1865)
Cluthia cluthae (Brady, Crosskey and Robertson, 1874)
Cytheropteron spp.
Elofsonella concinna (Jones, 1857)
Heterocyprideis sorbyana (Jones, 1857)
Krithe praetexta (Sars, 1866)
Leptocythere tenera (Brady, 1868)
Normanicythere leioderma (Norman, 1869)
Rabilis mirabilis (Brady, 1868)
Robertsonites tuberculatus (Sars, 1866)
Palmenella limicola (Norman, 1865)
Palmoconcha laevata (Norman, 1865)
Pterygocythereis coronata (Roemer, 1838)
Sarsicytheridea punctillata (Brady, 1865)
Sarsicytheridea bradii (Norman, 1865)

TABLE 3. Macrofossils in the Nørre Lyngby 2 core

Echinodermata
Strongylocentrotus droebachiensis (Müller, 1776)

Crustacea: Cirripedia
Balanus hameri (Ascanius, 1769)

Mollusca: Gastropoda
Cyclichina sp.
Epitonium greenlandicum (Perry, 1911)
Limacina retroversa (Fleming, 1823)
Oenopota incisula (Verrill, 1882)
Oenopota tenuicostata (G.O. Sars, 1878)
Turritella communis Risso, 1826
Tachyrhynchus erosus (Couthouy, 1838)

Mollusca: Bivalvia
Abra spp.
Abra prismatica (Montagu, 1803)
cf. *Delectopecten greenlandicus* (Sowerby, 1842)
Jupiteria minuta (Müller, 1776)
Kelliella miliaris (Philippi, 1844)
Macoma calcarea (Gmelin, 1790)
Nuculana pernula (Müller, 1799)
Parvicaradium ovale (Sowerby, 1840)
Pseudamussium septemradiatum (Müller, 1776)
Thracia sp.
Thyasira sp.
Yoldiella nana M. M. Sars, 1865
Yoldiella spp.

abrupt changes in lithology as expressed in the grain size distributions.

The transparent intervals in the seismic profile seem to correspond to intervals with relatively well-sorted sediments, either clay-dominated as in subunit IA (83–72 ms; 70.5–61 m) and in the lower part of subunit IIIB (22–16 ms; 18–12 m) or sand-dominated as in the lower part of unit II (58–45 ms; 48–38 m). The intervals characterised by bank structures seem to correlate with intervals with upwards increasing grain size: subunit IB (72–58 ms; 61–48 m), upper part of unit II (45–35 ms; 38–29 m), upper part of subunit IIIA (30–22 ms; 25–18 m) and in subunit IIIB (22–10 ms; 18–8 m).

The observed variations in the lithology and in the corresponding parts of the seismic profile are

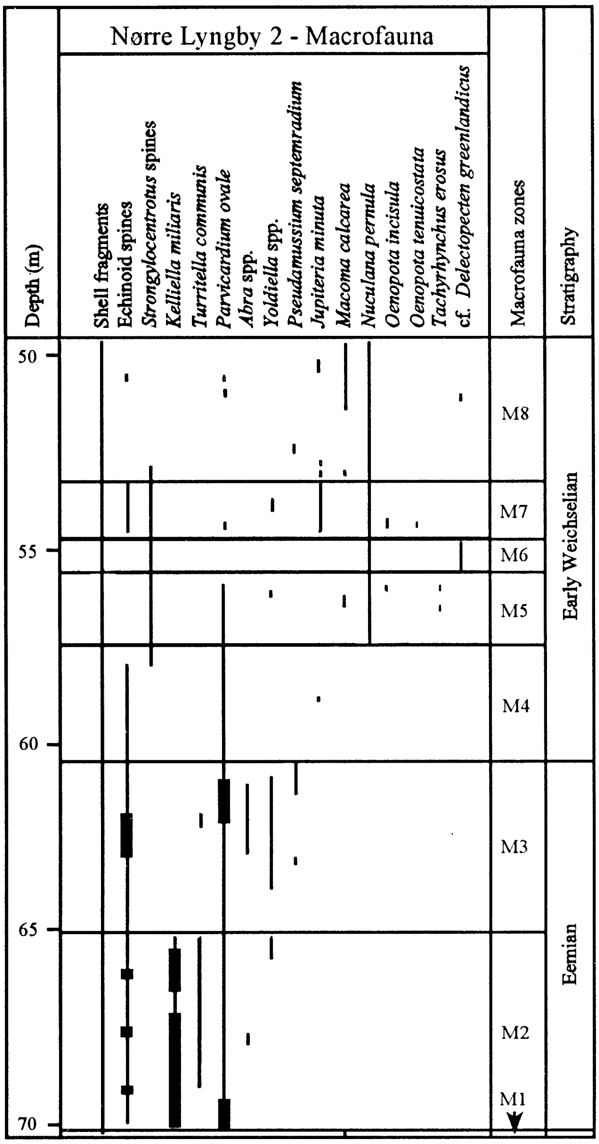

FIG. 10. Distribution of the macrofauna between 70.5 and 48.0 m depth in the Nørre Lyngby 2 core. The macrofaunal zonation (Zones M1–M8) is shown to the right.

interpreted as indications of variations in depositional environments. Two types of environment appear to be represented in the sequence, namely the transparant intervals with well-sorted sediments and the upwards coarsening intervals with bank architecture. The transparent intervals may represent environments with stationary current conditions and sediment supply, and the intervals with banks possibly correspond to environments with spatially varying currents and temporally increasing current strength.

The seismic and lithological data indicate that the sequence at Nørre Lyngby developed in depositional cycles with initial phases with stationary conditions, possibly marine environments with relatively deep water, and final phases with variable and increasing current velocities, possibly marine environments with depths shallowing through time. Unit I is the first cycle in the sequence followed by similar cycles in units II, IIIA and IIIB.

Two major changes in depositional environments are located at the base and at the top of the sandy unit II. It is remarkable that these changes do not appear to be accompanied by major erosion. The relief on these reflections seems to be generated as constructive features, namely as undulating or inclined surfaces of preceding depositional systems built up of bank structures.

Benthic Foraminifera and Ostracods

A total of 129 samples from the interval between 70.5 and 48.0 in the Nørre Lyngby 2 core were analysed for foraminiferal and ostracod contents. The sequence has been subdivided into 9 foraminiferal/ostracodal assemblage zones, Zones FO1–FO9 (Figs. 5–9), according to the definition by Salvador (1994).

Zone FO1 (70.5–69.90 m)

The high-density foraminiferal fauna (high number/100 g; Fig. 5) in this zone is dominated by the arctic species *Cassidulina reniforme* and *E. excavatum* s.l. (see above) together with a few other arctic and subarctic species such as *Stainforthia loeblichi* and *Nonionellina labradorica* (Figs. 5 and 7). Less than 100 valves of ostracods per 100 g sediment occurred in this interval. The marine boreo-arctic sublittoral species *Acanthocythereis dunelmensis* (see Athersuch *et al.*, 1989) is dominant, and the arctic species *Rabilis mirabilis* also occurs (Fig. 5). The assemblages in this zone reflect glacial marine environments during deposition.

Zone FO2 (69.90–67.89 m)

There is a marked decline in *E. excavatum* and *C. reniforme* at the base of Zone FO2 (Figs. 5 and 7). This marks a change from the arctic foraminiferal fauna in the underlying Zone FO1 to warmer water conditions in Zone FO2. The miliolids increase in Zone FO2 and there is a gradual increase in the amount of the boreal species *C. laevigata*, while the arctic *C. reniforme* gradually decreases through the lower part of the zone. Arctic species have completely disappeared in the middle and upper part of Zone FO2 and are replaced by boreal species (Fig. 7). *B. marginata* is now totally dominant together with accessory species such as *E. excavatum*, *C. laevigata*, *Hyalinea balthica* and *Cassidulina obtusa*. A change is also observed in the ostracodal fauna in the lower part of this zone. Arctic ostracods predominate at the base of Zone FO2, but the boreo-arctic species *Sarsicytheridea punctillata* gradually becomes dominant. The contemporaneous appearance of *Krithe praetexta* points to gradually deeper water conditions (Penney, 1993). The first part of zone FO2 thus seems to represent a transitional interval from the arctic conditions in Zone FO1 to full interglacial conditions in the upper part of zone FO2.

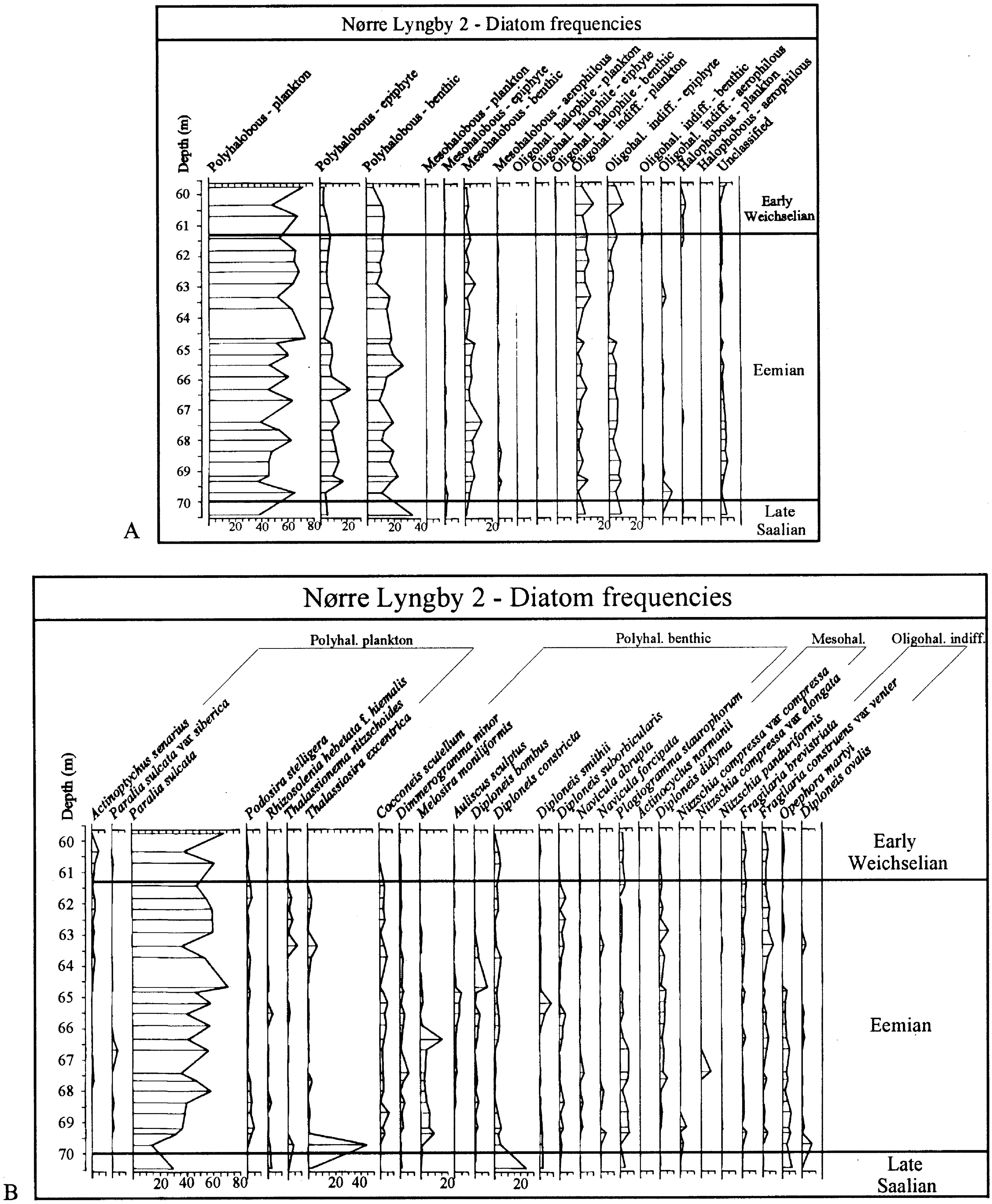

FIG. 11. **A**: Grouping of planktonic and tychoplanktonic diatom species (percentages) as well as all benthic forms except epiphytes and aerophilous lifeforms in the interval 70.5–59.5 m depth in the Nørre Lyngby 2 core. The interglacial interval is indicated to the right (boundaries in accordance with foraminiferal/ostracodal zonation). **B**: Percentage distribution of selected species of diatoms in the interval 70.5–59.5 m depth in the Nørre Lyngby 2 core. The interglacial interval is indicated to the right (boundaries in accordance with foraminiferal/ostracodal zonation).

Zone FO3 (NL–1) (67.89–66.01 m)

Through this zone there is a decrease in the amount of a number of temperate foraminiferal species (e.g., *B. marginata* and *C. laevigata*) and some even disappear completely (e.g., *C. obtusa*) (Fig. 5). The arctic species *C. reniforme* gradually re-appears and dominates the fauna in the middle part of the zone (Fig. 7).

TABLE 4. Diatom taxa mentioned in the text, Nørre Lyngby 2

Actinoptychus senarius (Ehrenb.) Ehrenberg, 1843
Actinocyclus normanii forma *normanni* (Greg. ex Greg.) Hust. ex Van Land., 1967
Auliscus sculptus (W. Sm.) Ralfs in Pritch, 1861
Cocconeis scutellum var. *scutellum* (Ehrenb., 1838)
Dimmerogramma minor var. *minor* (Greg.) Ralfs in Pritch, 1861
Diploneis bombus (Ehrenb.) Ehrenb. ex Cleve, 1894
Diploneis constricta (Grun.) Cleve, 1894
Diploneis didyma (Ehrenb.) Cleve, 1894
Diploneis interrupta (Kütz.) Cleve, 1894
Diploneis ovalis (Hilse) (Cleve, 1894)
Diploneis smithii (Bréb. ex W. Sm.) Cleve, 1894
Diploneis suborbicularis (Greg.) Cleve, 1894
Fragilaria brevistriata Grun. in Van Heurck, 1885
Fragilaria construens var. *venter* (Ehrenb.) Grun. in Van Heurck, 1881
Melosira moniliformis (O.F. Müll.) Ag., 1824
Navicula abrupta var. abrupta (Greg.) Donk., 1870
Navicula forcipata Grev., 1859
Nitzschia compressa var. *compressa* (J.W. Bail.) Boyer, 1916
Nitzschia compressa var. *elongata* (Grun.) Lange-Bertalot, 1987
Opephora martyi Herib., 1902
Paralia sulcata (Ehrenb.) Cleve, 1873
Paralia sulcata var. *siberica* (Ehrenb.) Grun., 1882
Plagiogramma staurophorum (Greg.) Heiberg, 1863
Podosira stelligera (J.W. Bail.) Mann, 1907
Rhizosolenia hebetata forma *hiemalis* Gran., 1905
Thalassionema nitzschoides (Grun.) Grun. ex Hustedt, 1932
Thalassiosira excentrica (Ehrenb.) Cleve, 1903

S. punctillata is still the dominant ostracod in Zone FO3, although *A. dunelmensis* increases in number and the arctic species *Normanicythere leioderma* appears for the first time. Zone FO3 is believed to represent a cooling of the water masses at the site. The indications of cooling in Zone FO3 represent true signals and are not a result of reworking of arctic specimens. First of all the temperate foraminiferal species decrease in concentrations or they disappear at the same time as the arctic species re-appear in the assemblages. Secondly, the specimens of the arctic foraminifera and the arctic ostracods are of different shape and size. Hence, they are not likely to have been reworked by the same process. This cooling event is called NL–1 (Seidenkrantz *et al*., 1995).

Zone FO4 (66.01–63.44 m)

The assemblages are again dominated by the boreal species *B. marginata* and *C. laevigata*, and a marked decrease in the arctic *C. reniforme* is observed (Figs. 5 and 7). The ostracod fauna is completely dominated by *S. punctillata*, and a few specimens of *Pterygocythereis coronata* are also found. *P. coronata* is a widespread benthic marine species in the Mediterranean, but it is also found south of NW Scotland (Athersuch, 1978). The only previous records of *P. coronata* in the North Sea region are from the two Danish Holsteinian sites Rugård and Hadsten (Knudsen and Penney, 1987). The number of ostracod valves per 100 g sediment decreases through the zone. In general, the foraminiferal and the ostracodal faunas in Zone FO4 indicate a return to full interglacial conditions.

Zone FO5 (NL–2) (63.44–63.01 m)

In this zone the arctic content increases, and *C. reniforme* (up to 31%) dominates the fauna together with the boreal *C. laevigata*, while there is a decrease in *B. marginata* (Figs. 5 and 7). The ostracod fauna is very sparse, less than 100 valves per 100 g sediment. The two dominant species are the boreo-arctic *S. punctillata* and *A. dunelmensis* (Fig. 5). The zone is suggested to represent another cooling event (NL–2; Seidenkrantz *et al*., 1995) in the marine environment (Fig. 7).

Zone FO6 (63.01–61.28 m)

No single species dominates the fauna in this zone. *B. marginata*, *C. laevigata*, *Bolivina spathulata* and *Pullenia osloensis* occur frequently. *E. excavatum* becomes abundant in the upper part and the amount of *C. reniforme* also increases towards the top (Figs. 5 and 7). Very low numbers of ostracod valves are found, most frequently *S. punctillata* and *A. dunelmensis* (Fig. 5). Zone FO6 appears to represent the return to full interglacial conditions, but with indication of cooling towards the top.

Zone FO7 (61.28–54.81 m)

All boreal species disappear in the lower part of Zone FO7 (Fig. 8). *E. excavatum* and *C. reniforme* become dominant, and high frequencies of the arctic species *Islandiella helenae*, *I. norcrossi* and *I. islandica* occur in the upper part as well. Ostracods are only present in the upper part of Zone FO7, the arctic species *N. leioderma*, *R. mirabilis* and *Elofsonella concinna* being characteristic for this interval (Fig. 6). Zone FO7 is interpreted to represent a return to arctic marine environments.

Zone FO8 (54.81–52.52 m)

E. excavatum is the single dominant species of this zone, and *C. reniforme* is relatively common. Arctic species decrease in number at the base of the zone, while the indifferent and transitional species group takes over (Fig. 8), and even the boreal species *B. marginata* is present in the lower part. *A. dunelmensis*, *N. leioderma*, *E. concinna* are common ostracod species, and in the lower part the boreo-arctic *S. punctillata* occurs together with *B. marginata* (Fig. 6). A similar co-occurrence is seen in the underlying interglacial zones. The assemblages in Zone FO8 reflect ameliorated temperature conditions, particularly in the lower part, and this interval presumably represents an interstadial period.

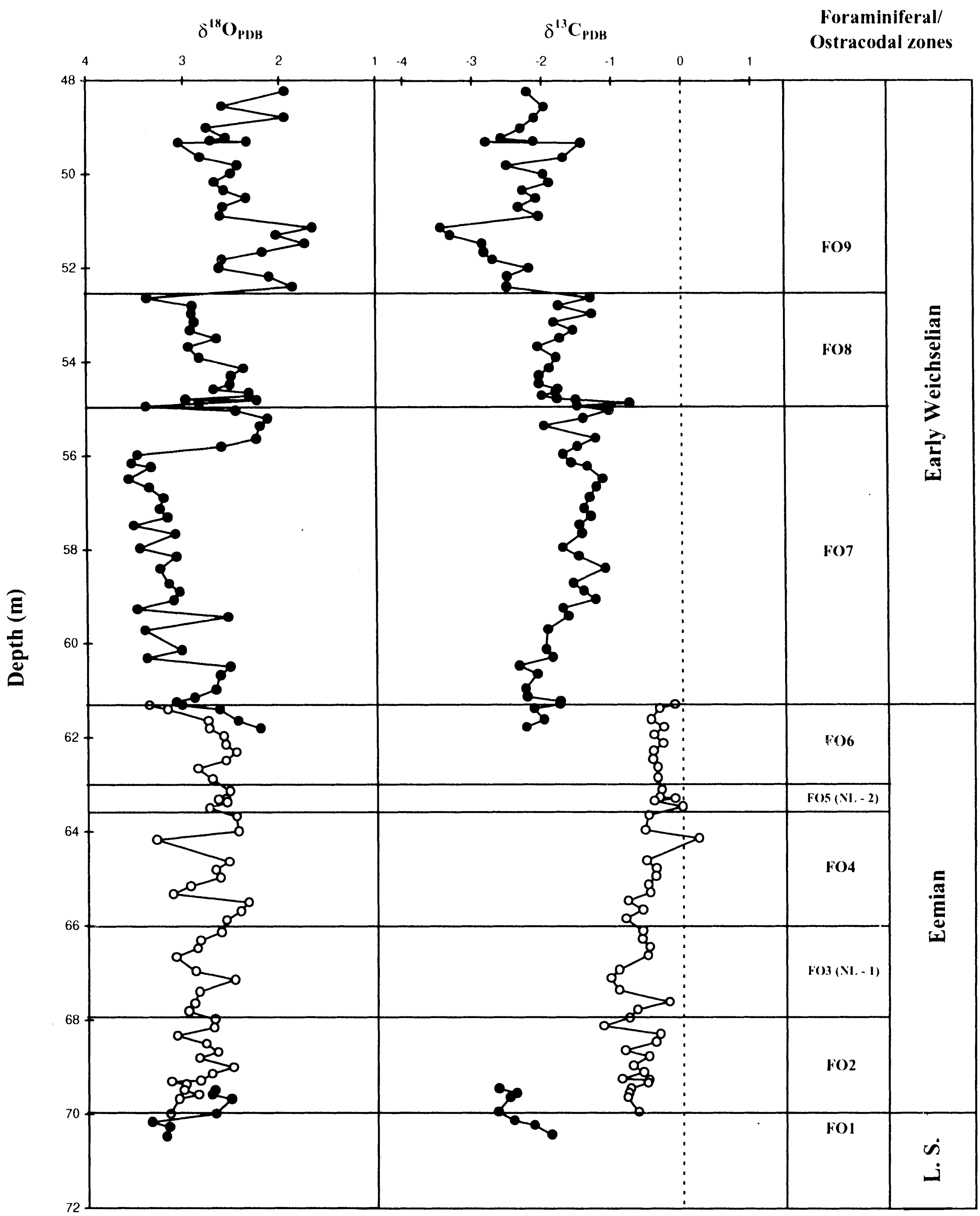

FIG. 12. Carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) isotopes for the interval 70.5–48.0 m depth in the Nørre Lyngby 2 core. Measurements were carried out on the benthic foraminiferal species *Cassidulina laevigata* in the interglacial interval (open rings) and on *Elphidium excavatum* in the glacial intervals (filled dots). Results are given relative to the PDB–standard. Foraminiferal/ostracodal zones are shown to the right.

TABLE 5. Results of Optically Stimulated Luminescence (OSL) datings from the Nørre Lyngby 2 and Skagen 3 cores.

Locality	Sample No.	OSL - age (ky)	OSL - age (ky) corr.	Lab. No.
Nr. Lyngby 2	K 29 (52.70–53.05 m)	64 ± 6	87 ± 10	R - 954805
Nr. Lyngby 2	K34 (61.00– 61.30 m)	72 ± 7	98 ± 10	R - 954806
Nr. Lyngby 2	K36 (64.35–64.50 m)	46 ± 5	60 ± 6	R - 964803
Nr. Lyngby 2	K40 (70.15–70.29 m)	48 ± 5	62 ± 6	R - 964804
Skagen 3	K102 (184.50–186.00 m)	51 ± 5	66 ± 6	R - 954803
Skagen 3	K103 (186.00–187.50 m)	98 ± 10	133 ± 15	R - 954804

The dates are corrected for the shallow trap effect (Mejdahl *et al.*, 1992).

Zone FO9 (52.52–48.23 m)

C. reniforme dominates the lower part of zone FO9, while *E. excavatum* characterises the remaining part of the zone. Arctic species are generally dominant throughout the zone, but a minor content of boreal species such as *B. marginata* and *Ammonia beccarii* is seen in two intervals (Fig. 8). Ostracods are frequent in the lower half of Zone FO9, the dominant species being *N. leioderma* and *E. concinna*, but very few valves are found in the upper half (Fig. 6). Zone FO9 is considered to represent a return to arctic conditions although temperature fluctuations seem to occur.

Planktonic Foraminifera

Planktonic foraminifera appear for the first time in the lower part of zone FO2, where they rapidly increase to make up a substantial part of the total (benthic + planktonic) foraminiferal fauna (Fig. 9). Planktonic foraminifera continue to occur through Zones FO2–FO6, i.e., during the entire succession with benthic indication of predominantly interglacial temperature conditions. The planktonic fauna is mainly represented by the arctic species *Neogloboquadrina pachyderma* (sinistral), but a few specimens of *N. pachyderma* (dextral), *Turborotalita quinqueloba* and *Globigerina bulloides* are registered as well. Very few planktonic foraminifera are found in the present Skagerrak, and these mainly belong to the boreal species *Globigerina uvula* (Ehrenberg) (Seidenkrantz, 1993a).

The high number of arctic planktonic foraminifera found together with boreal and boreo-lusitanian benthic foraminifera in the interglacial succession of the Nørre Lyngby 2 core seems to suggest a current system different from the present day circulation (Fig. 1). It is likely that the arctic planktonic foraminifera did not live and reproduce in the area together with warm water benthic faunas. They may rather have been continuously transported into the area with cold surface water currents from the Norwegian Sea. Thus, the planktonic foraminiferal content may be considered a measure of surface water inflow from the open Atlantic Ocean into the Skagerrak during the interglacial period. However, the co-existence of warm-water benthic foraminiferal assemblages and cold-water planktonic foraminifera in this relatively shallow shelf area is not yet fully understood.

Macrofaunas

The examined interval between 70.5 and 48.0 m depth in the Nørre Lyngby 2 core contains very few complete gastropods or bivalve valves, most being fragmentary. Many of the bivalve valves are of juveniles and some are decayed, particularly above 60 m. Comparison with the reports on the Skærumhede 1 (Nordmann, *in* Jessen *et al*., 1910) and the Skærumhede 2 (Petersen, *in* Bahnson *et al*., 1974) boreholes suggests that some of the breakage could have been caused by the action of overriding glacier ice, though reworking of some of the material cannot be excluded. Similar broken valves were reported in the Nørre Lyngby 1 borehole (Lykke-Andersen, 1987). A noteworthy feature leading to difficulty of identification is the paucity of hinge fragments of bivalves, particularly in the upper part of the examined section. Most of the material forms angular fragments, but the exterior of the fragmentary valves of *Parvicardium ovale* is generally slightly eroded. The sequence can be subdivided into eight macrofaunal assemblage zones, Zones M1–M8 (Fig. 10). The species are listed in Table 3.

Zone M1, the Macoma assemblage zone (70.5–70.17 m)

The lowest three samples, between 70.47 and 70.17 m, contained freshly broken bivalve fragments, probably entirely *Macoma calcarea*. According to the borehole log, the shells were *in situ* in the core. This assemblage reflects shallow, cold water marine conditions.

Zone M2, the Kelliella assemblage zone (70.17–65.33 m)

This zone is characterised by the bivalves *Kelliella miliaris*, *Parvicardium ovale*, the gastropod *Turritella communis* and by echinoid spines. *K. miliaris* is currently distributed in fully saline deep water with bottom temperatures over 5°C, chiefly between 100 and 1000 m depth from Lofoten and southern Iceland to NW Africa and the Mediterranean (Warén, 1989b; Peacock, 1993). It also occurs in the deeper parts of the Skagerrak and the northern North Sea (Jensen and Spärck, 1934). The impression of deep water is reinforced by the occurrence of *Yoldiella nana*, paired valves which were collected from between 65.18 and 65.55 m depth in the core. This bivalve is normally found in water depths greater than 100 m in the Skagerrak today (Warén, 1989a). A single specimen of the lusitanian to high-boreal planktonic pteropod *Limacina retroversa* was found at 66.33 m depth, suggesting the sea was open to the North Atlantic (Bé and Gilmer, 1977). However, *P. ovale* extends from West Africa into low-arctic waters in depths of less than 110 m (commonly less than 75 m) and *T. communis* is found from North Africa to Lofoten, usually at depths of less than 100 m. Overall, there is a suggestion of relatively deep water (perhaps >75 m) and (in the absence of the boreo-arctic species such as *Nuculana pernula*), sea temperatures similar to, or possibly slightly higher than those at present in the northern Danish area.

Zone M3, the Abra-Parvicardium assemblage zone (65.33–60.70 m)

There is a consistent occurrence of *P. ovale*, especially in the upper half of the zone, where it is joined by *Abra* spp. (probably chiefly *A. nitida*), *Yoldiella* spp., *Pseudamussium septemradiatum* and abundant plates and spines of echinoids. The presence of *A. nitida* suggests Atlantic rather than Polar water and *Yoldiella* spp. near normal marine salinity (Peacock, 1993). *P. septemradiatum* is an active epifaunal animal that extends northwards into the low-arctic of Finnmark (Sars, 1878) and, though it has been reported at water depths up to 183 m, it is usually found between 10 and 60 m. There is thus an indication of a decrease in water depth and, in the absence of warm water species, possibly somewhat lower temperatures than those pertaining to Zone M2.

Zone M4, the Parvicardium assemblage zone (60.70–57.30 m)

Apart from the consistent occurrences of *P. ovale* and echinoid spines, macrofaunal remains are uncommon in this assemblage zone. Environmental conditions may have been less favourable than those obtained during the deposition of Zone M3. The base of the unit coincides with a lithological change from well-sorted to less well-sorted sediment.

Zone M5, the Nuculana-Parvicardium assemblage zone (57.30–55.64 m)

Though the continued presence of *P. ovale* suggests an influence of Atlantic water, the consistent occurrence of *N. pernula* and spines of the echinoid *Strongylocentrotus droebachiensis* provide a cool to cold appearance to the fauna. At the present day *N. pernula* extends from the arctic to the coast of the Netherlands (Jensen and Spärck, 1934) and *S. droebachiensis* from the arctic to the North Sea (Mortensen, 1977). The interpretation of a cold environment is reinforced by the occurrence in the central part of the zone of *M. calcarea* (arctic to eastern North Sea, Jensen and Spärck, 1934) and *Tachyrhynchus erosus* (= *Turritellopsis erosus*), which has an arctic to subarctic distribution (Macpherson, 1971), extending south into east Finnmark in the NE Atlantic (Sars, 1878). *Oenopota incisula* is a cold water North American gastropod not now present in the eastern North Atlantic. It extends southwards from the arctic into deep water off the NE U.S.A. (Macpherson, 1971). In summary, the environment at the time of deposition seems to have been close to, but a little south of, the Polar Front.

Zone M6, the Nuculana-Delectopecten assemblage zone (55.64–54.90 m)

This is based on the occurrence of *N. pernula* together with fragments that are almost certainly those of *Delectopecten greenlandicus*, an arctic epifaunal species restricted to high-arctic (Ockelmann, 1958) environments. This would suggest water temperatures of 0°C or below, salinity close to near-normal marine, and a position north of the Polar Front.

Zone M7, the Jupiteria assemblage zone (54.90–52.64 m)

The *Jupiteria* Assemblage Zone is characterised by the bivalve *Jupiteria minuta* together with *Strongylocentrotus* and other echinoid spines. There are local occurrences of *P. ovale*, *Yoldiella* spp., *O. incisula*, *O. tenuicostata* and *Epitonium greenlandicum*. *O. tenuicostata* is a pan-arctic gastropod, extending into deep water southwards west of the British Isles, and *E. greenlandicum* has an arctic to low-boreal distribution (excluding the British Isles) (Bouchet and Warén, 1980; Smith and Heppell, 1991). *J. minuta* ranges from the British Isles to the arctic, but does not occur in the high-arctic (Ockelmann, 1958). Together with the occurrence of *P. ovale* and 'other echinoid spines' there is thus evidence for subarctic, but not high-arctic conditions, with a minor influence of Atlantic water.

Zone M8, the Nuculana-Macoma assemblage zone (52.64–48.79 m)

The consistent occurrence of *N. pernula* and *M. calcarea* in a low-diversity macrofauna suggest cool to cold conditions. A decayed valve of *M. calcarea* was collected from a subsample at 53.12–53.15 m. There is a suggestion of somewhat warmer water between 50.33 and 51.14 m where there are a few fragments of *Parvicardium* and *Jupiteria*, together with echinoid spines and plates (not *S. droebachiensis*). However, the occurrence of fragments of the high-arctic bivalve *Delectopecten greenlandicus* at 51.14 m suggests that there could have been reworking in this sector of the borehole.

Diatoms

A diverse diatom flora was found throughout the sequence (70.44–59.74 m, Fig. 11A and Fig. 11B), and in spite of the relatively low concentration of diatom valves approximately 180 species were identified. The entire assemblage is dominated by a polyhalobous tychoplanktonic species, *Paralia sulcata* (Fig. 11B), and no clear zonation of the diatom assemblage is possible. *P. sulcata* is a cosmopolitan coastal species which can be found quite far up estuaries as well as in coastal marine waters. It has a well silicified and robust frustule which may preserve it preferentially, resulting in its high relative numbers and allowing it to dominate assemblages in some sediments. A small number of other marine tychoplanktonic species are also present, *Actinoptychus senarius* and *Podosira stelligera*, and planktonic *Thalassionema nitzschoides* and *Thalassiosira excentrica.* All of these species reach $>5\%\sum D$. *T. excentrica* reaches $45\%\sum D$ at 68.70–68.73 m, dominating the level and suppressing the *P. sulcata* relative percentage value (Fig. 11B). *T. excentrica* has been described as oceanic through to saltmarsh in biotope by Denys (1991b). It has been mainly described as planktonic, though an epontic/benthic lifeform has also been noted. It would appear that it is planktonic in open water but can also live intertidally in saltmarsh conditions (Sullivan, 1978).

Of the marine planktonic forms found, the majority have also been reported from shallow waters and in the benthos. The only significant exception is *Rhizosolenia hebetata* f. *hiemalis* which is a true marine planktonic form, but it can also be found in the littoral zone. *R. hebetata* f. *hiemalis* is a cold water species (Hendey, 1964) and it is found at 11 levels throughout the sequence. It is present in very low numbers, or absent at those levels which the foraminifera indicate as cold phases.

The rest of the marine species are either classified as epiphytic or benthic. *Cocconeis scutellum*, an epiphyte commonly found attached to submerged aquatic vegetation, and *Dimmerogramma minor*, epipsammic, attached to sand grains, are consistently present almost throughout the sequence at values of ca. $5\%\sum D$. Both are widely distributed benthic marine littoral species.

Melosira moniliformis is consistently common in the lower part of the succession, reaching $>10\%\sum D$. Vos and de Wolf (1993) categorise *M. moniliformis* as a marine/brackish epiphyte. It can withstand desiccations often flourishing with intertidal exposure.

Within the marine (Polyhalobion) benthic group four epipelic species reach $\geqslant 5\%\sum D$, they are *Diploneis bombus*, *D. smithii*, *Navicula abrupta* and *N. forcipata*. Two other *Diploneis* species, *D. constricta* and *D. suborbicularis* also reach $\geqslant 5\%\sum D$ with *D. constricta* reaching $>20\%\sum D$ at the base of the sequence. *Plagiogramma staurophorum* is epipsammic in lifeform and is present throughout the sequence. All of these species are defined as aquatic by Denys (1991a) as opposed to 'commonly in periodic water or wet subaerial' conditions suggesting a subtidal but shallow water environment. Grain size analysis shows that sand makes up a very small fraction of the core sediment. The presence of episammic diatoms suggests that sand bodies occurred at the locality at the time of deposition.

Within the Mesohalobous group most of the species are found at very low percentages. The epiphytes together do not reach $5\%\sum D$. The Mesohalobous benthic group, which reaches $>10\%\sum D$ in the lower part of the sequence, is made up of mostly epipelic species with some epipsammic species. Only three species reach $>5\%\sum D$, they are *Diploneis didyma*, epipelon, which is present throughout the succession and *Nitzschia compressa* var. *compressa* and *N. compressa* var. *elongata* both of which are only present in the lower part of the sequence. There are two mesohalobous aerophilous species present, one of them *Diploneis interrupta* is present throughout the sequence but at low ($<3\%\sum D$) percentages. This brackish-marine shallow water to intertidal assemblage, though limited in diversity, suggests fringing mudflats and perhaps sand banks in the area.

The Oligohalobous halophile group is very poorly represented with only three species present, none of which reaches $>1\%\sum D$.

The Oligohalobous indifferent group is dominated by the planktonic and epiphytic species groups both of which reach $\geqslant 10\%\sum D$ at a number of levels. The tychoplankton is dominated by *Fragilaria construens* var. *venter* and *F. brevistriata*. *Opephora martyi*, another epipsammic taxa, is present at almost every level. It is present at $\geqslant 5\%\sum D$ in the lower part of the sequence but decreasing upwards to $\leqslant 1\%\sum D$. *Diploneis ovalis*, an Oligohalobous indifferent aerophilous species, is present at a number of levels but reaches $>5\%\sum D$ at 69.70–69.73 m. Freshwater (Halophobous) species are very sparse in the assemblage, but taken together with the Oligohalobous indifferent group they represent at least a part assemblage from a terrestrial source.

There are some Tertiary diatoms, both whole and fragments, present in the sediment. One species which has been identified is *Paralia sulcata* var. *siberica* (Mitlehner, pers. commun.), and there are fragments of other possibly Tertiary species also present. *P. sulcata* var. *siberica* is a species which is found in the Tertiary Fur-Formation deposits, which outcrop in NW Denmark to the south of Nørre Lyngby. The species is found in very low numbers in seven samples spread throughout the sequence.

The number and percentage of true marine forms in the assemblage is very low. There are fragments of assemblages from freshwater and estuarine environments. The overall assemblage appears to represent a littoral, subtidal assemblage with a small input from deeper water and consistent inputs from terrestrial sources. The presence of marine to marine/brackish, benthic and epiphytic forms, suggests a certain proximity of mudflat and saltmarsh environments. The wide range of salinity tolerance which exists among the dominant species is present throughout the sequence and continues on either side of the interglacial sediments, as defined by the foraminifera, emphasising the marine character of the sequence. There is a slight overall increase in planktonic forms and decrease in benthic forms upwards through the sequence. It may be that marginal mudflats are disappearing, or reducing in size in conjunction with a deepening of the water, but the disappearance of mudflats as source areas for littoral diatoms may on the other hand also have been caused by a lowering in sea level.

STABLE ISOTOPES IN BENTHIC FORAMINIFERA

Results of the stable isotope measurements on the foraminiferal species *E. excavatum* (in glacial deposits) and *Cassidulina laevigata* (in interglacial deposits) from the sequence between 70.5 and 48.0 m in the core are shown on Fig. 12.

Comparatively high $\delta^{18}O$ and $\delta^{13}C$ values in the late glacial period (Zone FO1) are followed by a depletion both in $\delta^{18}O$ and in $\delta^{13}C$ at the transition to the interglacial period (Zone FO2).

The oxygen isotope values are relatively low through the interglacial period (Zones FO2–FO6), but fluctuate in a cyclic pattern through the upper part of Zone FO3 and the lower part of FO4. A marked increase through the upper part of Zone FO6 presumably indicates a gradual cooling of the water masses, which is also reflected by the foraminiferal assemblages. The relatively low oxygen isotope values through most of the interglacial period may partly be linked to higher freshwater input from land, as also indicated by the diatom floras, but it may also be linked to the ice volume effect and a generally higher bottom water temperature. There is a slight gradual enrichment in $\delta^{13}C$ through the interglacial period.

Both the oxygen and carbon isotope values increase gradually in the initial part of the succeeding glacial period (Zone FO7), but a marked drop in $\delta^{18}O$ followed by a return to higher values occurs in the uppermost part of Zone FO7. After some major fluctuations in both oxygen and carbon isotope values at the Zone FO7/FO8 transition these become more stable, but with gradually increasing values through Zone FO8. There is a marked drop both in $\delta^{18}O$ and in $\delta^{13}C$ at the Zone FO8/FO9 boundary. Zone FO9 is characterised by large fluctuations, but in general both the $\delta^{18}O$ and the $\delta^{13}C$ are more depleted at the base than in the upper part of the zone. The changes in $\delta^{18}O$ values through the early glacial period (Zones FO7–FO9) are presumably determined by fluctuations in salinity in this glacial marine environment rather than in temperature. Differences in the meltwater supply may for instance result in changes in the stratification of the water column resulting in considerable changes in bottom water salinties.

In general, the benthic oxygen and carbon isotope values in the succession show relatively large fluctuations. Similar fluctuations have also previously been reported from marine Quaternary shelf records in this area (e.g., Seidenkrantz, 1993b; Seidenkrantz and Knudsen, 1997). It must be emphasised that nearshore isotope records as presented here cannot be directly compared with records from oceanic sites because freshwater discharge may affect the $\delta^{18}O$ significantly in these environments.

OPTICALLY STIMULATED LUMINESCENCE (OSL) DATING

OSL dates from four different levels in the Nørre Lyngby 2 core (Table 5) gave ages of between 60 ± 6 and 98 ± 10 ky. Both the OSL date from the lower glacial period (62 ± 6 ky) and that from the interglacial (60 ± 6 ky) indicate younger ages than expected for late Saalian and Eemian (ca. 130–115 ky) deposits. Low OSL ages seem to be a general problem for Danish Eemian marine sediments (Ditlefsen, 1991). However, the two OSL dates obtained for the succeeding the early glacial (98 ± 10 and 87 ± 10 ky) part of the Nørre Lyngby core would support an early Weichselian age for this deposit. The OSL dates thus suggest an Eemian age for the present interglacial.

Two OSL dates from a similar glacial-interglacial succession in the Skagen 3 core are included in Table 5 for comparison. An age of 133 ± 15 ky was obtained for the late Saalian (187.50–186.00 m depth), while a sample from the Eemian gave an age of 66 ± 6 ky (186.00–184.50 m) which is also younger than expected for that deposit. Unfortunately, it has not been possible to obtain enough material from the 'classical' Eemian localities (Skærumhede 1 and Apholm) for OSL dating, but a thermoluminescence (TL) date from the Eemian Interglacial interval in the Anholt II core (Risø Lab. No. R–914803) gave an age of 126 ± 10 ky (corrected for shallow trap effect; Vagn Mejdahl, pers. commun., 1996). However, TL dates both from the Nørre Lyngby 2 and the Skagen 3 cores show a large variability in the results suggesting serious problems with the bleaching of grains for that method (Mejdahl, pers. commun., 1996).

In contrast to this, the amino acid values both from Nørre Lyngby and from Skagen suggest significantly older ages than indicated by OSL dates from the same deposits, suggesting an age around 400 ± 100 ky (Sejrup, pers. commun., 1996). This age interpretation would imply that the interglacial deposits at Nørre Lyngby and Skagen are significantly older than hitherto believed. Both interglacial deposits were previously correlated with the Eemian by Lykke-Andersen (1987), Seidenkrantz *et al.* (1995) and Seidenkrantz and Knudsen (1997). A possible influence of the amino acid values by the chemical treatments of the sediment samples in the laboratory has been tested thoroughly without any indication of effects (Sejrup, in prep.). Furthermore, results of heat flow measurements in the nearby Nørre Lyngby 1 borehole showed no temperature anomalies for the sediments compared to other boreholes in the region (Niels Balling, pers. commun., 1996).

BIOSTRATIGRAPHICAL CORRELATION AND DISCUSSION

All the above analyses show that an interglacial period is represented in the material, including its climatic transition from a previous glacial period and the succeeding transition to the following glacial period. A biostratigraphical correlation of the foraminiferal/ostracodal zones and the macrofaunal zones with pollen zones from the same succession (Glaister and Gibbard, this volume) is presented in Fig. 13 together with the seismic and the chronostratigraphic units.

The Interglacial Period

The interglacial foraminiferal/ostracodal Zones FO2–FO6 and the macrofaunal Zones M2–M3 correspond to the pollen Zones NL–1b to NL–4 (Glaister and Gibbard, this volume) and to the lower part of the lithological unit a and the seismic unit IA (Fig. 13).

Zones FO2–FO6 and M2–M3 correspond to Zone 7 of the Nørre Lyngby 1 core (Lykke-Andersen, 1987),

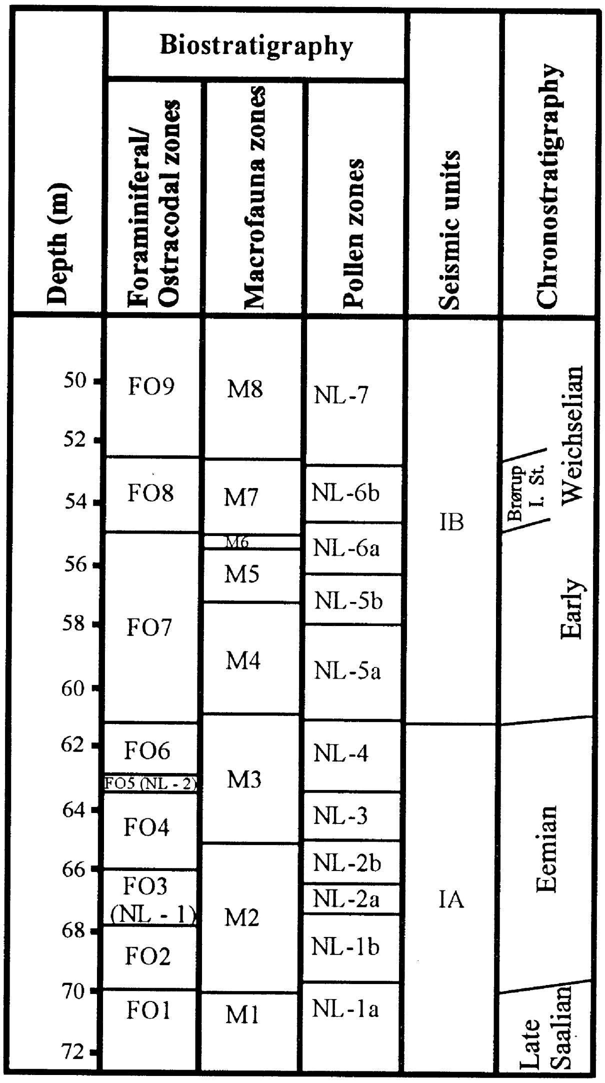

FIG. 13. Biostratigraphical correlation between the foraminiferal/ ostracodal zones and the macrofaunal zones with the pollen zones (Glaister and Gibbard, this volume) in the interval 70.5–48.0 m depth in the Nørre Lyngby 2 core. The seismic units and the chronostratigraphic units are shown to the right.

while the underlying Zone FO1 and Zone M1 can be correlated with Zone 8a of this core. The very sharp faunal change at the glacial-interglacial transition in the Nørre Lyngby 2 core might be an indication of a minor time gap in the deposition. The apparent absence of mollusc Zone M2 in Nørre Lyngby 1 core would also suggest an unconformity at the base of the interglacial in that core.

As a whole, the macrofaunas in Zones M2 and M3 also correspond to those found in the Eemian succession in the classic Skærumhede 1 borehole (Jessen *et al*., 1910). The long run of the bivalve *Kelliella miliaris* in the Nørre Lyngby 2 core, however, contrasts with its occurrence only near the base of the interglacial *Turritella terebra* Zone in the Skærumhede 1 borehole, and suggests that part of the sequence could either be missing or very thin in the basal part of the latter.

The warm interglacial succession is interrupted by two cool intervals (NL–1 and NL–2) as indicated by the foraminiferal assemblages. The lower and most pronounced of these coolings (Zone FO3) is also clearly identified in the ostracod assemblages, and there is even an indication of cooling in the pollen assemblage (Glaister and Gibbard, 1998, Zone NL–2a). There is no supporting evidence of these cooling events in the macrofauna (Fig. 10), possibly because of the small sample size and consequent under-representation of the molluscs. It should be noticed, however, that very cold bottom water seems to be excluded in NL–1 because of the continuous occurrence of *Turritella communis* (minimum summer surface temperature today about 13°C) and *Kelliella miliaris* (minimum about 5°C) in Zone M2. The upper cooling event in the interglacial is only indicated by an increase in the amount of arctic foraminifera in the assemblages (Zone FO5, Figs. 7 and 13).

A generally higher amount of planktonic foraminifera in the lower part of the interglacial (Fig. 9) would suggest an initially more open oceanic connection, and maybe also deeper water. A shallowing in water depth towards the top is also indicated by the macrofauna in Zone M3 and possibly by the coarsening upwards in the sediments through the lower part of lithological unit a (seismic unit IA, Fig. 4). The diatoms do not, however, give any clear signal, but the disappearance of marginal mudflats as source areas for the transported littoral diatoms might be caused by a lowering in sea level.

Very diverse boreo-lusitanian foraminiferal assemblages have also been described from a 25–60 m thick Eemian Interglacial deposit, which is represented over large areas in North Jutland (generally found in the interval ca. 190–100 m below present day sea level; Knudsen and Lykke-Andersen, 1982; Knudsen, 1984, 1985, 1992) and in the Kattegat area (at ca. 75–70 m b.s.l.; Seidenkrantz 1993b). Some of the characteristic benthic foraminiferal species in these deposits are *B. marginata*, *C. laevigata*, *Hyalinea balthica*, *C. obtusa*, *Melonis barleeanus* and the lusitanian species *Quinqueloculina padana*, the latter species being considered a diagnostic species for Eemian deposits in the region (Knudsen, 1992). The same species are present throughout most of the interglacial succession in the Nørre Lyngby 2 core. A detailed comparison of the faunal succession in the interglacial at Nørre Lyngby with the neighbouring Apholm core (Knudsen, 1984) also shows a striking similarity. For instance, the occurrence of *C. obtusa* in only the lower part and the appearance of *P. osloensis* and *B. spathulata* in the upper part of the interglacial successions are examples of common features. A similar early occurrence of *C. obtusa* is also observed in the Eemian sequence of the Anholt core (Seidenkrantz, 1993b) as well as in the Skagen 3 core (Seidenkrantz and Knudsen, 1997).

There are, however, also differences between the foraminiferal assemblages in the interglacial deposit of the Nørre Lyngby 2 core and the 'classical' Eemian assemblages from Skærumhede 1 and Apholm in northern Denmark. The two cooling events in the

Nørre Lyngby sequence have for instance not been found in any of these successions. An explanation for this may be that the sampling was considerably less dense in the older cores. However, similar cooling events have been observed in an interglacial sequence from the Skagen 3 core, which has been correlated with the Eemian (Seidenkrantz *et al.*, 1995; Seidenkrantz and Knudsen, 1997) in spite of the fact that amino acid measurements in this interglacial show high values similar to those in the Nørre Lyngby 2 core.

Similar rapid climatic fluctuations within the Eemian have also been recorded from the southern Greenland Sea and from the Norwegian Sea (Sejrup *et al.*, 1995; Fronval and Jansen, 1996, 1997). Although the interpretation of the Eemian section of the GRIP ice core has been questioned (e.g., Peel, 1995), it should be mentioned that high amplitude climatic variations were recorded from that core as well (e.g., GRIP Members, 1993). Comparable Eemian climatic changes have also been demonstrated from the European pollen and rock magnetic records (e.g., Tzedakis *et al.*, 1994; Thouveny *et al.*, 1994; Field *et al.*, 1994).

The planktonic foraminifera in the Skagen 3 sequence, which represents a deeper water facies than any of the 'classical' Eemian sites in the area, are similar to those found in the interglacial deposits of the Nørre Lyngby 2 core. The Eemian sequence at Apholm also shows similarity in the planktonic contents (see Seidenkrantz and Knudsen, 1997).

The high amount of arctic planktonic foraminifera in the interglacial deposits at Nørre Lyngby suggests the existence of a current system different from the present day circulation system in the area (Fig. 1). Surprisingly high percentages (40–90%) of the arctic *N. pachyderma* (sinistral) and fluctuating climatic conditions were also recorded by Fronval and Jansen (1996, 1997) in Eemian deposits in the Norwegian Sea (i.a., ODP Core 644). Today similar high percentages only occur further to the west and the north between the Arctic and Polar Fronts (Johannessen *et al.*, 1994). In contrast to this, McManus *et al.* (1994) reported very low frequencies of sinistrally coiled *N. pachyderma* and stable conditions during the Eemian off the west coast of Ireland (Core V29–191). These observations would suggest a reversed circulation system during the Eemian Interglacial with input of Norwegian Sea waters into the Skagerrak area.

During the Eemian an open marine connection seems to have existed from the Skagerrak area through the Baltic to the White Sea (e.g., Zans, 1936; Raukas, 1991; Zagwijn, 1996) resulting in a free interchange of water between the Atlantic and the Arctic Ocean. This may have created a shutdown of the Norwegian Coastal Current and an increased input of Norwegian Sea waters into the present area. A westward shift of the North Atlantic Current has also previously been suggested (Sejrup *et al.*, 1995; Seidenkrantz *et al.*, 1995; Fronval and Jansen, 1996, 1997).

Unfortunately, ostracods have not been examined in the previously described Eemian deposits in northern Denmark. An Eemian ostracod fauna with clear southern affinity was reported from a tidal flat sequence at Højer in southwest Jutland (Penney, 1989), and shallow water ostracod faunas from a number of Holsteinian sites in Jutland have also been studied (Knudsen and Penney, 1987). Due to the difference in water depths, none of these are comparable with the ostracod assemblages in the interglacial deposits of the Nørre Lyngby 2 core. There is, however, some similarity between the Nørre Lyngby ostracods and the faunas from Inner Silver Pit core 81/52A in the southern North Sea, where boreal faunas with dominance of *S. punctillata* and *A. dunelmensis* occur (Ingram, 1998). The interglacial deposit at Inner Silver Pit was correlated with the Hoxnian Interglacial on the basis of pollen (Scourse *et al.*, 1998), and amino acid results point at a correlation with isotope stage 9 (Kristensen *et al.*, 1998). The amino acid ratios from Inner Silver Pit are quite close to those obtained in the interglacial deposits at Nørre Lyngby, but neither the pollen flora nor the foraminiferal faunas would support a correlation.

A correlation of the interglacial pollen record in the Nørre Lyngby 2 core with the record from the terrestrial Eemian in Denmark bears sufficient similarity to allow correlation with the Eemian (Glaister and Gibbard, 1998), although some differences are found as well. However, according to the pollen assemblages, the Skagen 3 core only includes the latter part of the Eemian Interglacial.

It is also important to stress that there is a difference in thickness between the interglacial deposits at Nørre Lyngby and Skagen and the 'classical' Eemian successions at Skærumhede and Apholm (Figs. 1 and 2). At Skærumhede and at Apholm the Eemian intervals have thicknesses of 40 and 50 m, respectively, while the interglacial units at Nørre Lyngby and Skagen are only 8.5 and 5 m thick, respectively. Although no data are available by which subsidence rates can be estimated quantitatively, it is considered likely that differential subsidence can have played a significant role in this Fennoscandian Border Zone, which is known for its tectonic activity. However, an overdeepening of such elongate depressions could also have been effected by a NW drainage of glacier ice into the Skagerrak area. If the topography of the surface of the pre-Quaternary (Fig. 2) is taken to image the pattern of Quaternary differential subsidence, maybe combined with glacial erosion, it appears that the Nørre Lyngby and Skagen sites are located on highs whereas Skærumhede and Apholm are located in a low. This difference may have had an impact on the depositional pattern including the resulting thickness of the deposits. However, no definitive conclusions can be drawn concerning the control of the thickness variation during the Eemian Interglacial, but the oceanic circulation and the sedimentation pattern may have been quite different from that in the Holocene and at present in the Skagen area (Conradsen and Heier-Nielsen, 1995; Knudsen *et al.*, 1996).

The Early Glacial Period

The foraminiferal/ostracodal Zones FO7–FO9 and the macrofaunal Zones M4–M8 correspond to the pollen Zones NL–5a to NL–7 (Glaister and Gibbard, 1998), to the upper part of the lithological unit a and to the seismic unit IB (Fig. 13).

The early glacial succession in the Nørre Lyngby 2 core (Zones FO7–FO9 and M4–M8) corresponds to Zone 6 and the lowermost part of Zone 5 in the Nørre Lyngby 1 core (Lykke-Andersen, 1987). Lykke-Andersen (1987) correlated this sequence with part of the Middle Weichselian. This correlation is, however, not supported by the present study, in which a continuous sedimentation from the interglacial into the succeeding glacial period is suggested at the Zone FO6–FO7 transition. The Zones FO7–FO9 in the Nørre Lyngby 2 core are thus suggested to be early Weichselian in age (see below).

A gradual change to arctic environments is seen in the foraminiferal assemblages at the base of Zone FO7, and arctic conditions prevail throughout the zone. The macrofauna indicates much colder conditions in Zone M5 than in M4, and in M6 the environment was truly high-arctic. Extremely cold conditions thus seem to have prevailed just previous to the succeeding interstadial period, which is clearly indicated by both the foraminifera and ostracods (Zone FO8), the macrofauna (Zone M7) and the pollen assemblages (Glaister and Gibbard, 1998, Zone NL–6b). Also pollen Zone NL–5b (corresponding to the middle part of Zone FO7, Fig. 13) indicates ameliorated temperature conditions. This has not been registered in any of the other palaeo-ecological parameters.

In addition, the stable isotope data reflect changed environmental conditions in the uppermost part of Zone FO7 (corresponding to the high-arctic Zone M6, see Figs. 12 and 13). An estuarine circulation system with freshwater discharge in the surface waters and a cold saline counter-current at the bottom may have prevailed during the lower part of Zone FO7. The marked decrease in $\delta^{18}O$ towards the top might be a result of reduced stratification of the water column during this extremely cold period. During the following interstadial (Zone FO8) the stratification seems to have been gradually re-established, interrupted by a new change at the transition to the arctic Zone FO9.

The foraminiferal assemblages indicate climatic fluctuations even within the uppermost arctic Zone FO9. Two intervals with a few warmer water foraminiferal species are recorded in the middle and upper part, and also macrofaunas suggest slightly warmer water in the middle part of the zone. There is also a marked change in the oxygen isotope values after the lower third of the zone, indicating a change in the environment, presumably caused by a higher meltwater discharge to the area.

The seismics and lithological data indicate that the early glacial succession (upper part of lithologic unit a and seismic unit IB) corresponds to an upwards coarsening interval with bank structures with spatial current variations and temporal increase in current velocity. A shallowing towards the top is also suggested by the foraminiferal assemblages in Zone FO9.

CHRONOSTRATIGRAPHY

From the above correlations and datings it is obvious that there is a serious problem in the age interpretation of the studied succession in the Nørre Lyngby 2 core. The biostratigraphical data and the OSL dates suggest correlation with the interglacial-glacial deposits in the Skagen 3 core and with the 'classical' Eemian Interglacial sequences and the succeeding early Weichselian in the area, including the Brørup Interstadial. Amino acid ratios, however, point to a much higher age for the deposits, i.e., about 400 ky (Sejrup, pers. commun., 1996).

Biostratigraphical correlation is a restricted tool for Quaternary stratigraphy, because similar successions of fauna may immigrate into the northwest European shelf area every time the environmental conditions are the same. The biostratigraphical evidence for climatic conditions warmer than at present in the benthic assemblages in the interglacial, however, seems to be a strong argument for a correlation with the Eemian. Hitherto, this is the only interglacial in which the Atlantic Current is known to have transported warm Atlantic water masses into the Skagerrak-Kattegat area.

An Eemian age for the interglacial seems to be supported by the seismic data. Seismic reflections image surfaces of acoustic impedance contrasts, which in turn are controlled by changes in lithology. In sequences deposited without extensive interruptions changes in lithology are likely to be minor, and hence reflection amplitudes are expected to be relatively low. Where substantial breaks in the sedimentation occur it is likely that the change in lithology will be more pronounced, and the corresponding reflection will have a relatively high amplitude. Where extensive breaks in sedimentation are accompanied by erosion, reflections are most likely to be truncated at the surface of erosion.

The high amplitude reflections at the base and top of seismic unit II may correspond to hiatuses, but the absence of truncated reflections is an indication of breaks in sedimentation not being followed by noteworthy erosion. Thus, the seismic evidence is not compatible with the conception of seismic unit I belonging to an interglacial older than the Eemian. The extremely high water content in the interglacial sediments also seems to support a relatively young age of the deposit. Repeated overriding of glacier ice would thus presumably have lead to a lowering in water contents.

SUMMARY AND CONCLUSION

Environmental oscillations in a marine succession from the Nørre Lyngby 2 core in northern Denmark have been deduced on the basis of the foraminiferal, ostracodal, macrofaunal and diatom contents in addition to stable isotopes and lithology. The understanding of the architecture of the layering and the variation in depositional environment in the area is supported by a reflection seismic profile across the core site.

The succession between 70.5 and 48.0 m in the core is included in the lithologic unit a. This interval has been subdivided into nine foraminiferal/ostracodal zones (FO1–FO9), eight macrofaunal zones (M1–M8) and two seismic subunits (IA–IB), while the diatom contents did not allow any zonation. The above zones and units have been correlated with the pollen zonation (Zones NL–1a to NL–7) of the same sequence presented in Glaister and Gibbard, (1998).

Climatic oscillations from glacial environments through a period of full interglacial conditions and back to glacial environments were recorded. The boreal to boreal-lusitanian interglacial period is interrupted by two cool intervals as indicated by the foraminiferal assemblages. The lower and most pronounced cooling is also clearly shown by changes in the ostracod and the pollen assemblages (Glaister and Gibbard, 1998).

The succeeding early glacial period with faunal indication of mainly arctic marine climatic conditions is interrupted by a period of ameliorated temperature conditions as indicated by both foraminifera, ostracods, macrofauna and pollen. Fluctuations in the isotopic data presumably indicate changes in the stratification of the water column due to variation in the supply of meltwater to the area.

A chronostratigraphical interpretation of the marine Nørre Lyngby succession is problematic. A biostratigraphical correlation with well-known interglacial deposits in the same area and the OSL dates suggest an Eemian age for the interglacial deposits and thus a correlation of the succeeding early glacial amelioration with the Brørup Interstadial. Amino acid values, however, suggest a much older age for the deposit (Sejrup, pers. commun., 1996).

In a sequence encompassing glacial-interglacial cycles, i.e., periods with substantial variations in relative sea level and with possibilities for glaciations in lowstand periods, erosional features are to be expected. The high-resolution seismic profile renders no evidence for any major erosional events, and the seismic data would thus support a chronostratigraphical interpretation with a minimum of hiatuses, i.e., an Eemian age for the interglacial interval and an early Weichselian age for the overlying glacial marine succession.

Further absolute dating, including additional methods, needs to be carried out and compared with the biostratigraphy in order to reach to a complete understanding of the chronostratigraphy of the area.

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