Géographie physique et Quaternaire

Marine High Resolution Records of the Last Interglacial in Northwest Europe: A Review

Paléo-environnements marins au dernier interglaciaire dans le nord-ouest de l'Europe

Hoch auflösende marine Schichten aus dem letzten nordwest-europäischen Interglazial : ein Überblick.

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Volume 48, Number 2, 1994

URI: https://id.erudit.org/iderudit/032993ar
DOI: https://doi.org/10.7202/032993ar

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Publisher(s)

Les Presses de l'Université de Montréal

ISSN

0705-7199 (print)
1492-143X (digital)

Explore this journal

Cite this article

Seidenkrantz, M.-S. & Knudsen, K. L. (1994). Marine High Resolution Records of the Last Interglacial in Northwest Europe: A Review. *Géographie physique et Quaternaire*, *48*(2), 157–168. https://doi.org/10.7202/032993ar

Article abstract

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Géographie physique et Quaternaire, 1994, vol. 48, n° 2, p. 157-168, 7 fig.

MARINE HIGH RESOLUTION RECORDS OF THE LAST INTERGLACIAL IN NORTHWEST EUROPE: A REVIEW

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ABSTRACT The last Interglacial in Northwest Europe (the Eemian) corresponds to stable oxygen isotope substage 5e (*ca.* 130-115 ka BP). Foraminiferal studies from northern Denmark suggest that deglaciation after the Saalian Glacial (stage 6) occurred gradually over a period of about 3000 years. Data from borings on the island of Anholt show that the deglaciation was interrupted by a climatic fluctuation equivalent to the Allerød-Younger Dryas-Preboreal cycle at the Weichselian-Holocene transition (stage 2/1). The environmental interpretation of the foraminiferal data when compared to that of the deep sea stable isotope stratigraphy indicates that this climatic oscillation may have been a global event. An initial sea level rise of about 50-60 m occurred at the Saalian-Eemian transition (stage 6/5e at about 130 ka BP) and the assemblages indicate that the sea level rose further in the middle part of the Eemian prior to a gradual drop in sea level in the Late Eemian. The Eemian/Weichselian boundary (stage 5e/5d at about 115 ka BP) was characterized by a major sea level drop and a temperature decrease from lusitanian to boreal conditions. The final change to fully glacial conditions did not occur until the Early-Middle Weichselian transition (stage 5/4 at about 74 ka BP).

RÉSUMÉ *Paléo-environnements marins au dernier interglaciaire dans le nord-ouest de l'Europe.* Le dernier interglaciaire dans le nord-ouest de l'Europe (l'Éémien) correspond au stade isotopique 5e (d'environ 130-115 ka BP). Les études sur les foraminifères effectuées dans le nord du Danemark indiquent que la déglaciation s'est réalisée graduellement sur environ 3000 ans après le Saalien (stade 6). Les données obtenues des forages dans l'île de Anholt démontrent que la déglaciation a été interrompue par une fluctuation climatique correspondant au cycle Allerød-Dryas inférieur-Préboréal à la transition Wechselien-Holocène. L'interprétation environnementale des données sur les foraminifères comparée à la stratigraphie isotopique marine démontre que cette oscillation climatique était à l'échelle mondiale. La hausse initiale du niveau marin de 50 à 60 m a eu lieu à la transition entre le Saalien et l'Éémien (stade 6/5e vers 130 ka BP) et les assemblages montrent que la hausse s'est poursuivie à l'Éémien moyen avant une baisse graduelle à l'Éémien supérieur. Aux confins de l'Éémien-Weichselien (stade 5e/5d vers 115 ka BP), il y eut une importante baisse du niveau marin accompagnée d'une diminution des températures, passant ainsi de conditions climatiques lusitaniennes à des conditions boréales. L'établissement des conditions glaciaires ne s'est fait qu'à la transition entre le Weichselien inférieur et le Weichselien moyen (stade 5/4 vers 74 ka BP).

ZUSAMMENFASSUNG *Hoch auflösende marine Schichten aus dem letzten nordwesteuropäischen Interglazial: ein Überblick.* Die letzte Interglazialzeit in Europa (Eem) entspricht dem stabilen Sauerstoff-Isotopen-Unterstadium 5e (vor rund 130,000-115,000 Jahren). Foraminiferen-Untersuchungen von Nord-Dänemark deuten darauf hin, dass das Abschmelzen nach der Saale-Eiszeit (Stadium 6) allmählich über eine Periode von ungefähr 3000 Jahren erfolgte. Bohrdaten von der Insel Anholt zeigen, dass das Abschmelzen durch Klimaschwankungen ähnlich denen des Alleröd-Jüngere Dryas-Präboreal Zykluses zur Zeit des Weichsel-Holozän Überganges (Stadium 2/1) unterbrochen wurde. Korreliert man Foraminiferen-Befunde von Bohrungen auf Anholt mit isotopenstratigraphischen Daten aus der Tiefsee, ergibt sich, dass diese Klimaschwankungen vermutlich von globalem Ausmass waren. Während des Saale-Eem Überganges (Stadium 6/5e vor rund 130,000 J.) stieg der Meeresspiegel zunächst um 50-60 m. In der mittleren Eem-Zeit hob er sich möglicherweise erneut, bevor er im späten Eem allmählich zurückging. Der Übergang vom Eem zur Weichsel (Unterstadium 5e/5d vor rund 115,000 J.) war gekennzeichnet durch eine starke Senkung des Meeresspiegels bei einem gleichzeitigen Rückgang der Temperatur von lusitanischen zu borealen Verhältnissen. Der endgültige Wechsel zu vollständig eiszeitlichen Bedingungen erfolgte erst am Übergang von der Frühen zur Mittleren Weichseleiszeit (Stadium 5/4 vor rund 74,000 J.).

Manuscrit reçu le 30 septembre 1993; manuscrit révisé accepté le 14 décembre 1993
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INTRODUCTION

The last Interglacial in Northwest Europe is named the Eemian Interglacial after the River Eem in the Netherlands, and was studied for the first time more than a century ago (Harting, 1874). The Eemian period is defined on the basis of pollen spectra from the type locality near the city of Amersfoort in the Netherlands (Zagwijn, 1961). At the type locality the lower boundary to the preceding glacial period, the Saalian, is located where the subarctic park landscape is replaced by a closed forest, while the upper boundary to the Weichselian Glacial is located where the forest is again replaced by a more open vegetation.

The correlation of the Eemian Interglacial with oxygen isotope substage 5e was demonstrated by Shackleton (1969), Mangerud *et al.* (1979) and Turon (1984). This implies a dating of the Eemian interglacial to about 130-115 ka BP following the chronology of Martinson *et al.* (1987). This accords with Müller's (1974) estimate for the duration of the Eemian Interglacial of at least 11,000 years based on varve and pollen stratigraphy from northern Germany.

Marine sediments from the Eemian in Northwest Europe can be divided into two main groups. In the Netherlands, northern Germany and southern Denmark shallow water deposits, containing foraminiferal and ostracod faunas, indicate a relatively large area where water depths did not exceed 40-50 m during the Eemian (Fig. 1). The marine sediments in this area only represent a minor portion of the Eemian, and neither the Saalian-Eemian (stage 6/5e) transition nor the Eemian-Weichselian (substage 5e/5d) transition are represented in the marine sediments (Konradi, 1976; Knudsen, 1985b, 1988; Penney, 1989).

In northern Denmark, however, a large, relatively deep, marine sedimentary basin existed during the period from the Late Saalian to the Middle Weichselian (oxygen isotope stages 6-3) (Knudsen, 1985a; Lykke-Andersen and Knudsen, 1991). The maximum paleo-water depth of this basin was about 100 m in the main part of the basin. The basin extended along a northwest-southeast axis from the Skagerrak into the Kattegat and is interpreted as a structural feature related to subsidence under tensional stress perpendicular to the Fennoscandian Border Zone (H. Lykke-Andersen, 1987). Extensive subsidence resulted in deposition of an apparently continuous marine shelf sequence in this basin spanning a period from the Late Saalian, through the Eemian, and into the Early and Middle Weichselian (Fredericia and Knudsen, 1990; Lykke-Andersen and Knudsen, 1991). Relatively dense sampling in extremely thick marine Eemian (up to 60 m) and Early Weichselian (20-40 m) deposits enable high resolution studies of the paleoecological development through this period.

MATERIAL

The data reviewed in this paper originate from studies on the foraminiferal content of twenty borings from northern Denmark examined in the years 1982-1992 (Knudsen and Lykke-Andersen, 1982; Knudsen, 1984, 1985a; A.-L. Lykke-Andersen, 1987; Seidenkrantz, 1993a, b) The material from the borings consisted of core- and ditch cutting samples. Core samples with a high sample density were available from the three boreholes, Anholt II, Anholt III and Apholm, which were selected as representative in the present study.

Close sampling of the 8-9 m thick marine Saalian-Eemian sequence (Seidenkrantz, 1993a, b) enables us to obtain a very high resolution record of paleoenvironmental and paleoclimatic changes for this period of time. Except for a few intervals with no recovery, the distance between the samples seldom exceeds 10 cm, which corresponds to a sample for approximately every 500 years. In some sections samples were studied at much closer intervals corresponding to a time gap of 20-100 years between samples (estimated from sediment accumulation rates) (Figs. 2, 3).

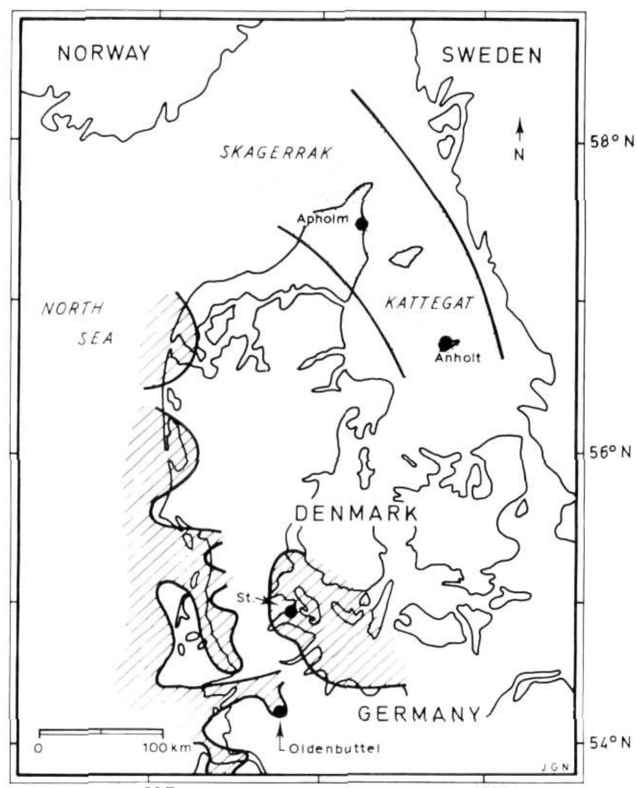

FIGURE 1. The maximum extent of the Eemian transgression in Denmark and northern Germany and the location of sites mentioned in the text. The stipple marks a deeper marine Eemian facies (about 100 m water depth) deposited in a presumably structurally controlled northwest-southeast trending basin across northern Denmark. The hatching indicates Eemian shallow marine coastal facies (0-40 m water depth) to the south and southwest (after Konradi, 1976; Streif, 1984; Penney, 1989; Knudsen, 1992; see also Fig. 6a for location of study area) St. = Stensigmose.

Localisation des sites mentionnés dans le texte et limite maximale de la transgression marine éémienne au Danemark et en Allemagne du Nord. La trame en pointillé délimite les faciès marins profonds de l'Eémien (environ 100 m) vraisemblablement mis en place dans un bassin sédimentaire qui s'inscrit dans une structure orientée NW-SE. Les zones hachurées identifient les faciès marins côtiers peu profonds (0-40 m) de l'Eémien localisés dans le sud et le sud-ouest. (modifiée de Konradi, 1976; Streif, 1984; Penney, 1989; Knudsen, 1992; voir aussi la fig. 6a pour la localisation de la région à l'étude) St. = Stensigmose.

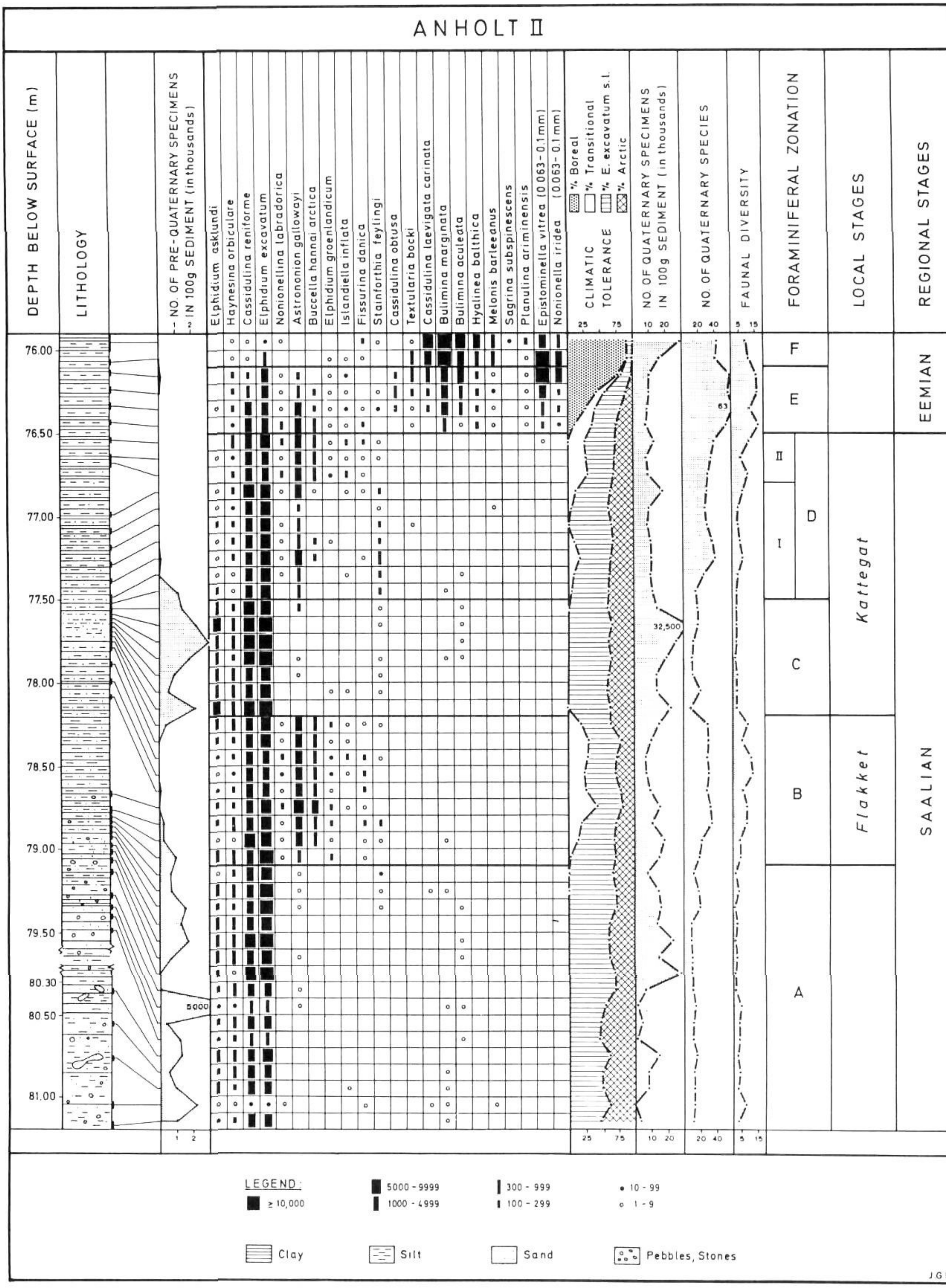

FIGURE 2. Anholt II boring: foraminiferal zones, faunal parameters and concentrations per 100 g sediment of selected benthic foraminifera. *Elphidium excavatum* s.l.: mainly *E. excavatum*, forma *clavata*. Pre-Quaternary foraminifera are mainly re-worked from the Maastrictian (after Seidenkrantz, 1993a).

Forage d'Anholt II: diagramme simplifié de la distribution et de la concentration par 100 grammes de sédiments de quelques foraminifères benthiques. Elphidium excavatum *s.l.: principalement* E. excavatum, *forma* clavata. *Les foraminifères pré-quaternaires proviennent principalement d'une faune remaniée du Maastrichien (d'après Seidenkrantz, 1993a).*

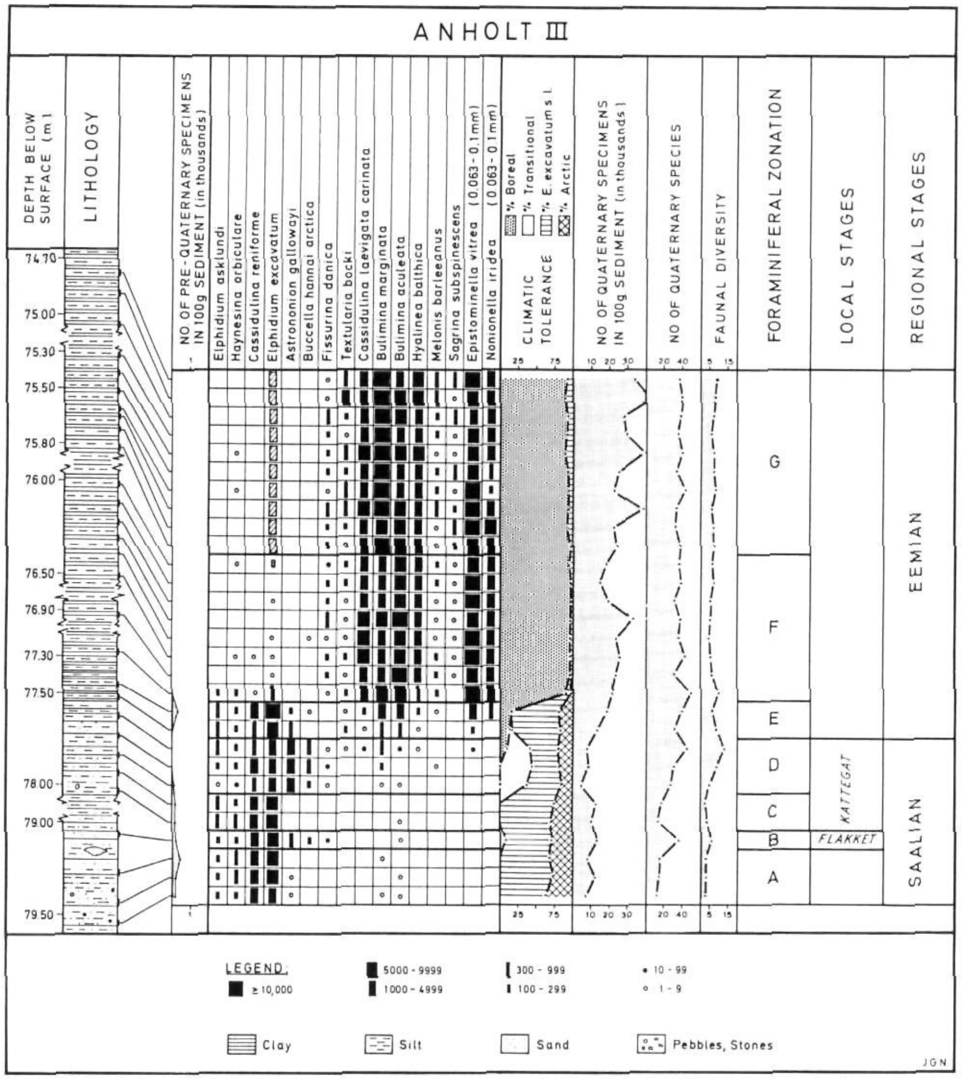

FIGURE 3. Anholt III boring: foraminiferal zones, faunal parameters and concentrations per 100 g sediment of selected benthic foraminifera. *Elphidium excavatum* s.l.: hatched signature represents dominance of forma *selseyensis*; filled in signature represents dominance of forma *clavata*. Pre-Quaternary foraminifera are mainly re-worked from the Maastrictian (after Seidenkrantz, 1993a).

Forage d'Anholt III : diagramme simplifié de la distribution, de la zonation et de la concentration par 100 g de sédiments de quelques foraminifères benthiques. Elphidium excavatum *s.l. : la zone hachurée représente la dominance de la forme* selseyensis *; la zone en noir représente la dominance de la forme* clavata. *Les foraminifères pré-quaternaires proviennent principalement d'une faune remaniée du Maastrichien (d'après Seidenkrantz, 1993a).*

In the Apholm boring the Eemian sequence is about 50 m thick. The sample intervals vary considerably (see Fig. 4), and the time resolution thus ranges from a few hundred to some thousand years.

METHODS

The samples for the foraminiferal analysis were treated in the laboratory using standard techniques (Meldgaard and Knudsen, 1979; Feyling-Hanssen *et al.*, 1971). Normally only the foraminifera in the 1.0-0.1 mm fraction were studied, though in the Anholt borings the fraction between 0.063 and 0.1 mm was also examined for additional species. The two species, *Epistominella vitrea* and *Nonionella iridea*, dominated the fine-grained fraction (Figs. 2, 3). These species were not present in the 0.1-1.0 mm fraction. Other species, which were only found in small numbers in the 0.063-0.1 mm fraction and which were also present in the coarser fraction, were only counted in the 0.1-1.0 mm fraction. As the total foraminiferal assemblage was derived from two different fractions in the Anholt borings the data are presented as actual counts instead of percentages (Figs. 2, 3) as for the Apholm (Fig. 4).

The material contained almost solely benthic foraminifera. In the Anholt borings these have been divided into groups representative of the recent North Atlantic faunal provinces (climatic tolerance): boreal (lusitanean to low/mid boreal), transitional (mid/high boreal to subarctic) and arctic (Figs. 5, 6a). *Elphidium excavatum* s.l. is shown as a separate curve, as the arctic (*clavata*) and boreal (*selseyensis*) forms have not been counted separately, but an estimate of which form dominated was made for each sample.

The stratigraphical allocation of the material is based on biostratigraphical correlation and amino acid measurements carried out at the Bergen Amino acid Laboratory (Sejrup and Knudsen, 1993; Seidenkrantz, 1993a). Stable isotope measurements from the Anholt borings are published by Seidenkrantz (1993a).

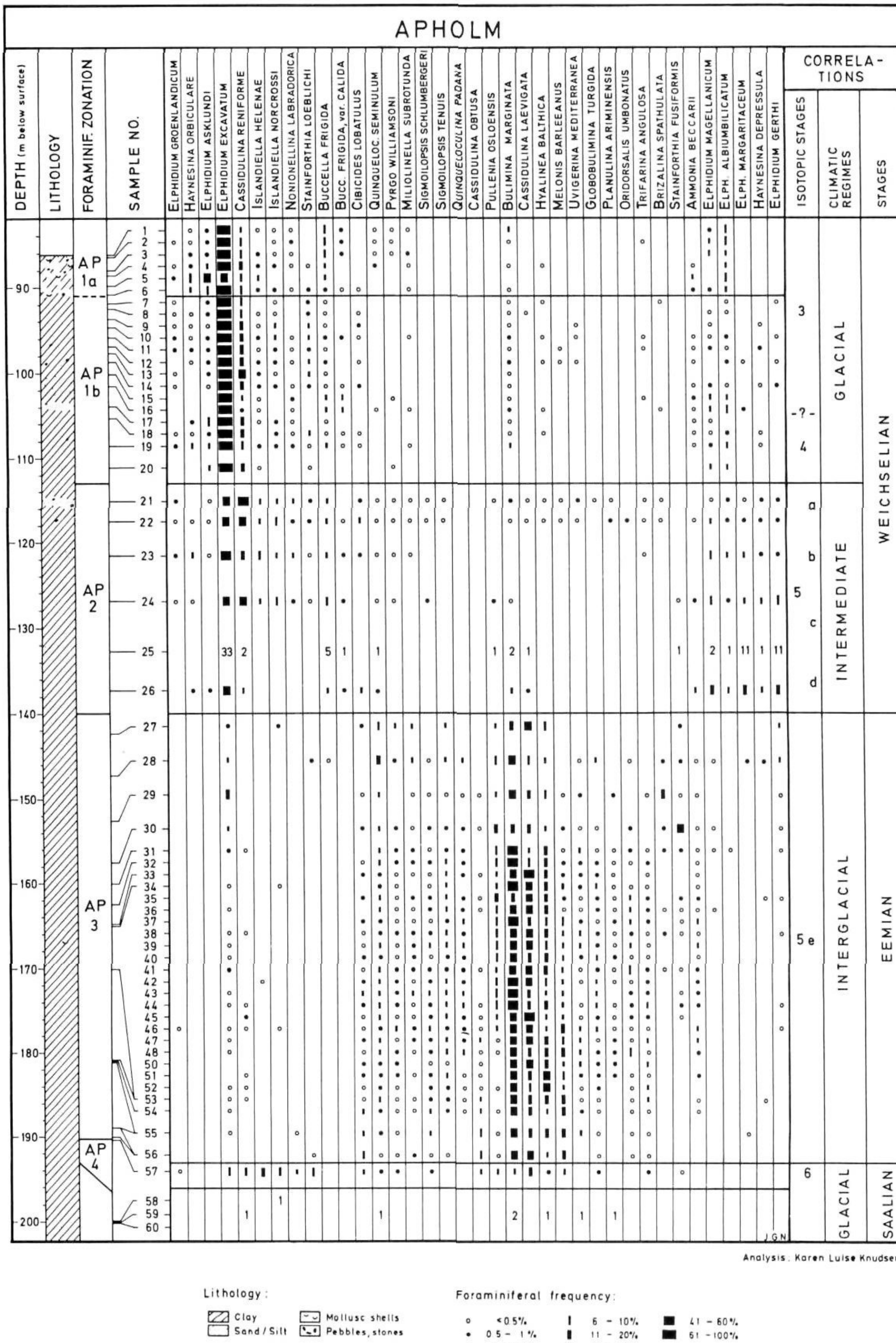

FIGURE 4. Apholm boring: relative frequency distribution of selected benthic foraminiferal species. Sample 25 presented as actual counts because of the low number of specimens (after Knudsen, 1984).

Forage d'Apholm : distribution de l'abondance relative de quelques foraminifères benthiques. Le spectre de l'échantillon 25 illustre les dénombrements bruts, en raison du faible nombre d'individus (d'après Knudsen, 1984).

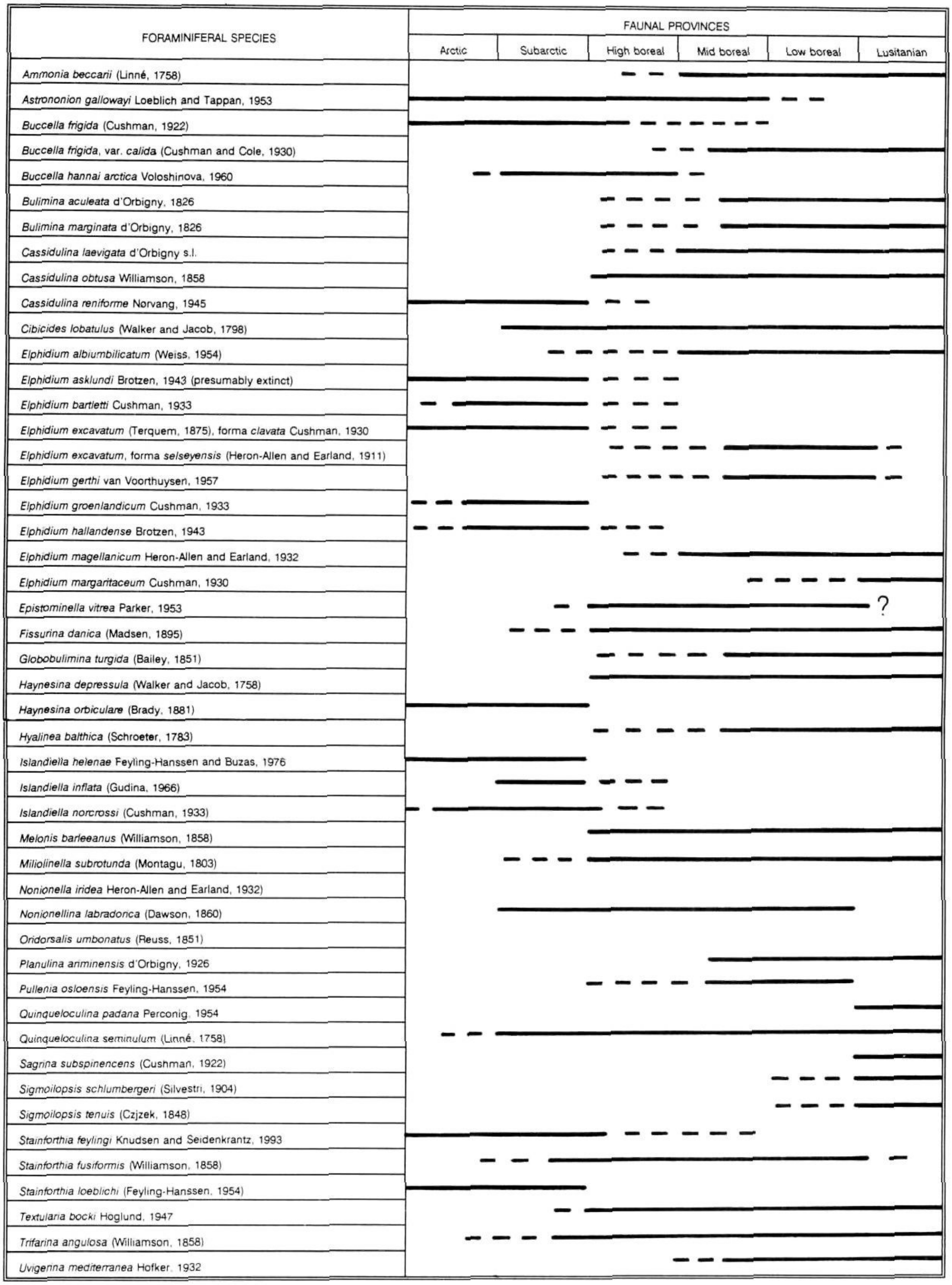

FIGURE 5. List of foraminifera mentioned in text and figures: species and preferred Northeast Atlantic faunal provinces. Faunal provinces are partly after Feyling-Hanssen (1955) and ecological data are from Nørvang (1945), Jarke (1960, 1961), Nagy (1965), Gudina and Evzerov (1973), Feyling-Hanssen (1983), Murray (1991) and Conradsen *et al.* (1993). *Nonionella iridea*: distribution badly known, *Oridorsalis umbonatus*: deep sea species.

Liste des foraminifères mentionnés dans le texte et les figures : espèces et provinces fauniques de l'Atlantique du Nord-Est. Les provinces fauniques sont en partie de Feyling-Hanssen (1955) et les données écologiques sont de Nørvang (1945), Jarke (1960, 1961), Nagy (1965), Gudina et Evzerov (1973), Feyling-Hanssen (1983), Murray (1991) et Conradsen et al. *(1993).* Nonionella iridea*: distribution mal connue,* Oridorsalis umbonatus *: espèce d'eau profonde.*

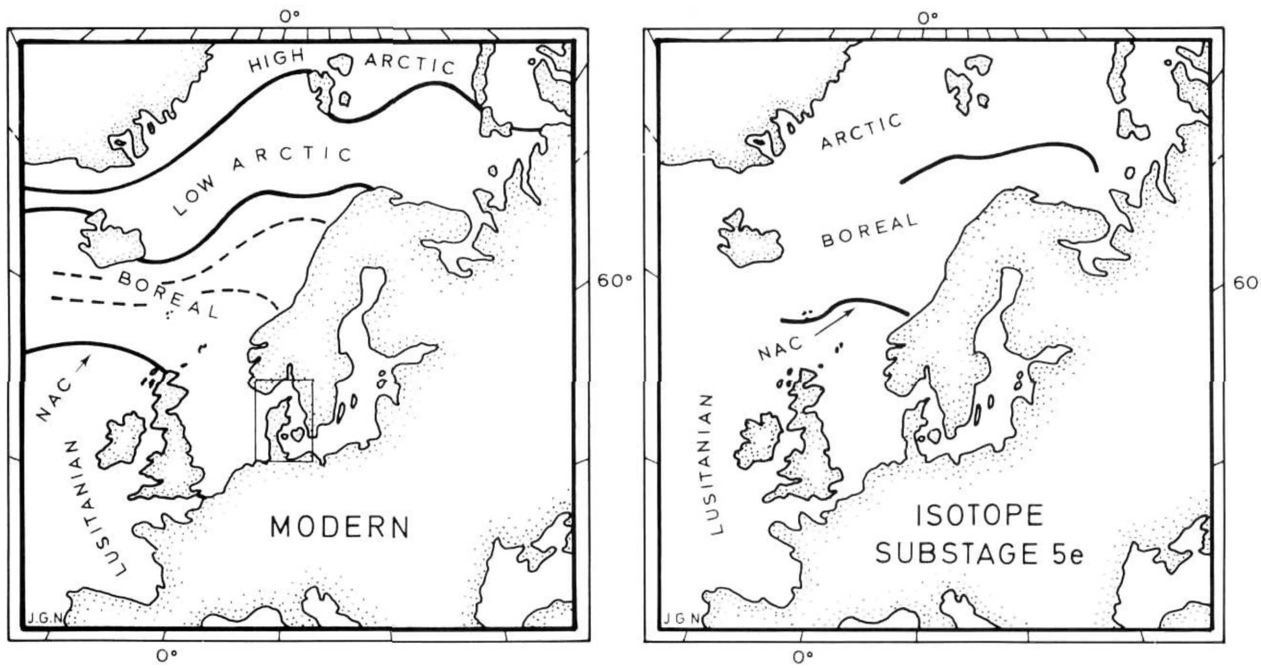

FIGURE 6. A) Modern faunal provinces (revised after Feyling-Hanssen, 1955). The dotted lines indicate subdivision of the boreal faunal province into low boreal (warmest), mid-boreal and high boreal (coldest) subprovinces. Rectangle outlines the study area (Fig. 1). NAC = North Atlantic Current. B) Suggested distribution of faunal provinces in the Northwest European Atlantic region during the Eemian (isotope substage 5e) (after Sejrup, in prep.). NAC = North Atlantic Current.

Les provinces fauniques modernes (modifiées de Feyling-Hanssen, 1955). Les lignes pointillées délimitent les sous-provinces à l'intérieur de la province faunique boréale: boréale inférieure (la plus chaude), boréale médiane et boréale supérieure (la plus froide). Le rectangle identifie la région à l'étude (fig. 1). NAC = Courant de l'Atlantique Nord. B) Reconstitution de la répartition des provinces fauniques de la région de l'Atlantique du Nord-Ouest durant l'Éémien (stade 5e), selon Sejrup, en prép.). NAC = Courant de l'Atlantique Nord.

CLIMATIC OSCILLATION AT THE SAALIAN-EEMIAN TRANSITION (STAGE 6/5e)

It is well known that the final part of the Late Weichselian was characterized by oscillations between colder and warmer periods (*e.g.* Mangerud *et al.*, 1974; Bard *et al.*, 1987; Dansgaard *et al.*, 1989; Lotter, 1991). Similar oscillations had not previously been described from the Saalian/Eemian boundary (isotope stage 6/5e) in marine, shelf sediments. Benthic foraminifera from the Anholt II and III borings from the small Danish island Anholt (Fig. 1), however, indicate that the Saalian-Eemian (isotope stage 6-5e) transition was in fact characterized by a climatic oscillation equivalent to the Allerød-Younger Dryas-Preboreal cycle at the Weichselian-Holocene transition (Seidenkrantz, 1993a).

The lower part of the marine section (Zone A; Figs. 2, 3) is characterized by a low diversity fauna dominated by the arctic species *Elphidium excavatum*, forma *clavata* and *Cassidulina reniforme*. The appearance of boreal-arctic species (corresponding to high boreal to subarctic faunal provinces, Fig. 5, 6) such as *Astrononion gallowayi* and *Buccella hannai arctica* and the gradual disappearance of ice-rafted material (pebbles and stones) in Zone B (Figs. 2, 3) indicate ameliorated conditions representing an interstadial designated by the local name the "Flakket Interstadial" (Seidenkrantz, 1993a). Zones C and D are characterized first by the disappearance and later by the gradual reappearance of these boreal-arctic species. The interval presumably represents an initial climatic deterioration to extreme arctic conditions followed by a gradual amelioration during a stadial period. This stadial has been given the local name, the "Kattegat Stadial" (Seidenkrantz, 1993a).

In Zone E a gradual but extensive faunal change to domination of boreal and lusitanian species such as *Bulimina aculeata, Bulimina marginata* and *Cassidulina laevigata carinata* Silvestri infers a rapid and major temperature increase from the arctic to subarctic environments of Zones C and D to the boreal-lusitanian conditions of zones F and G. The appearance of the relatively deep water species *Bulimina* spp. and *Melonis barleeanus* indicate that the temperature increase was accompanied by a major increase in water depth, that may well have been of the same magnitude (50-60 m), as indicated by sea level records (Chappell and Shackleton, 1986). The boundary between the Saalian and the Eemian is located at the boundary between Zone D and Zone E. Zone E is thus considered to represent the warming at the beginning of the Eemian, but fully interglacial conditions were not attained until the deposition of the sediments associated with zones F and G.

The succession and duration of the climatic cycles at the Saalian-Eemian transition can be compared with the duration of the climatic oscillation of the Allerød-Younger Dryas-Preboreal cycle at the Weichselian/Holocene boundary. Estimates based on sediment accumulation rates indicate that both the Flakket Interstadial (Zone B) and the Kattegat Stadial (Zones C and D), as well as the final amelioration at the beginning of the Eemian (Zone E) each had a duration of about 1000 years (Seidenkrantz, 1993a). This compares with the duration of the deglaciation during the Late Weichselian (the Allerød-Younger Dryas-Preboreal cycle) as the Allerød, the Younger Dryas and the Preboreal each had a duration of about 1000 radiocarbon years (Mangerud *et al.*, 1974; Bard *et al.*, 1987; Berger *et al.*, 1987; Dansgaard *et al.*, 1989; Lotter, 1991). The Flakket Interstadial (Zone B) is thus interpreted to correspond to the Allerød Interstadial, and the Kattegat Stadial (Zones C and D) is interpreted to be comparable to the Younger Dryas Stadial. Zone E is considered equivalent to the Preboreal period of the early Holocene.

The paleo-environmental signal obtained from the sediment and the foraminiferal assemblages may be correlated to the environmental record of the deep sea stable isotope records. The arctic Zone A may be correlated to the period between stable oxygen isotope events 6.2 and 6.01 of Pisias *et al.* (1984) and Martinson *et al.* (1987), after the initiation of deglaciation and the first sea level rise (Figs. 2, 3 and 7). The global sea level would probably have been too low to allow marine influence in the area during the minimum sea level at isotope event 6.2 (*cf.* Chappell and Shackleton, 1986; Shackleton, 1987; Martinson *et al.*, 1987). The ameliorated period of the Flakket Interstadial (Zone B) is correlated to the negative 6.01 oxygen isotope event, while the temperature deterioration and following amelioration of the Kattegat Stadial correspond to the positive peak in ^{18}O between 6.01 and 6.0. The rapid warming that followed the Kattegat Stadial is correlated to the enrichment of ^{18}O between isotope events 6.0 and 5.53 (Seidenkrantz, 1993a).

The 6.01 peak and the following positive excursion can be recognized in deep sea oxygen isotope records from both the Atlantic and the Pacific Oceans (*e.g.* Shackleton and Matthews, 1977; Shackleton *et al.*, 1983; Shackleton, 1987; Mackensen *et al.*, 1989). The correlation of the fluctuations of the foraminiferal assemblages at the Saalian-Eemian transition in the Anholt borings (Figs. 2, 3 and 7) with deep sea stable isotopic records, thus, suggests that the environmental signal seen in the faunas is the result of a global phenomenon.

SEA LEVEL FLUCTUATION IN THE EEMIAN

MIDDLE EEMIAN

During the Eemian the foraminiferal faunas from the paleo-embayment in northern Denmark were dominated by *B. marginata, B. aculeata, C. laevigata* s.l. and *Hyalinea balthica* (Figs. 3, 4). These species indicate a boreal to lusitanian paleoenvironment with water depths of about 100 m and water temperatures at least 2-3°C higher than at present (Knudsen, 1992). Estimates based on sedimentation rates indicate that Zone G from the Anholt III boring represents the Middle Eemian (Seidenkrantz, 1993a). The increase of *B. marginata* and *Sagrina subspinescens* indicate that it was a period of reduced oxygen content in the bottom waters, possibly as a result of increased water depth.

Evidence for an increased water depth during the Middle Eemian is supported by data from the Apholm boring in northern Denmark (Fig. 1). The boring contains an about 140 m thick, presumably almost continuous, Saalian to Middle Weichselian sequence (Fig. 4) (Knudsen, 1984). The entire Eemian Interglacial appears to be present (Zone AP3), with the exception of the initial warming that is represented by Zone E in the Anholt borings (Fig. 7). At Apholm there is an increase in frequency of the two deeper water species *Pullenia osloensis* and *Quinqueloculina padana* in the middle part of the Eemian Zone AP3. This interval of increased water depth may correspond to Zone G from Anholt.

The change in water depth within the Eemian in northern Denmark may be correlated with fluctuations in water depth recognized in southern Danish and northern German shallow water deposits from Stensigmose and Oldenbüttel (Fig. 1) (*cf.* Konradi, 1976; Knudsen, 1985b). Here an initial transgression is interrupted by a decrease in water depth of about 10 m and a second transgression with an increase in water depth of about 20 m (*cf.* Knudsen, 1985b). The validity of this correlation may in the future be checked through pollen analysis of the northern Danish material. A comparison with the detailed pollen and varve stratigraphy from northern Germany (Müller, 1974; Menke, 1985) will presumably establish a very accurate correlation between the two areas.

Fluctuations in the deep sea oxygen isotope record within isotope substage 5e have been observed in several records from the Norwegian Sea and the Atlantic and Pacific oceans (Hays *et al.*, 1976; Shackleton, 1977; Kellogg *et al.*, 1978; Duplessy *et al.*, 1980; Shackleton *et al.*, 1983; Ramm, 1988; Haake and Pflaumann, 1989; Sarnthein and Tiedemann, 1990). These records reflect an enrichment in ^{18}O within substage 5e separating two isotope events correlatable to 5.53 and 5.51 of Martinson *et al.* (1987), and are presumably synchronous with a fluctuation in the Huon sea level curve documented by Chappell and Shackleton (1986). The Huon sea level curve shows a regressive-transgressive cycle between isotope events 5.53 and 5.51 of about the same order of magnitude as the decrease in water depth documented from the shallow water deposits in Northwest Europe (*cf.* Chappell and Shackleton, 1986). If the sea level variations indicated by these different records are indeed the same, they would indicate that a global oscillation in the sea level occurred during the Middle Eemian.

LATE EEMIAN

The foraminiferal succession from the Apholm boring reveals that the sea level rise in the middle part of the Eemian must have been followed by a gradual decrease in water depth during the last part of the Interglacial. This decrease in water depth is indicated by lower percentages of the relatively deep water species such as *Uvigerina mediterranea, Globobulimina turgida, Oridorsalis umbonatus* and *M. barleeanus* and an increase in the relatively shallow water species *Elphidium gerthi* (Fig. 4). The drop in water depth amounts to approximately 15 m in the end of the Eemian (Fig. 7) (Knudsen, 1992), and the interval may correspond to a period of increasing $\delta^{18}O$ content just after the isotope event 5.53 of Martinson *et al.* (1987).

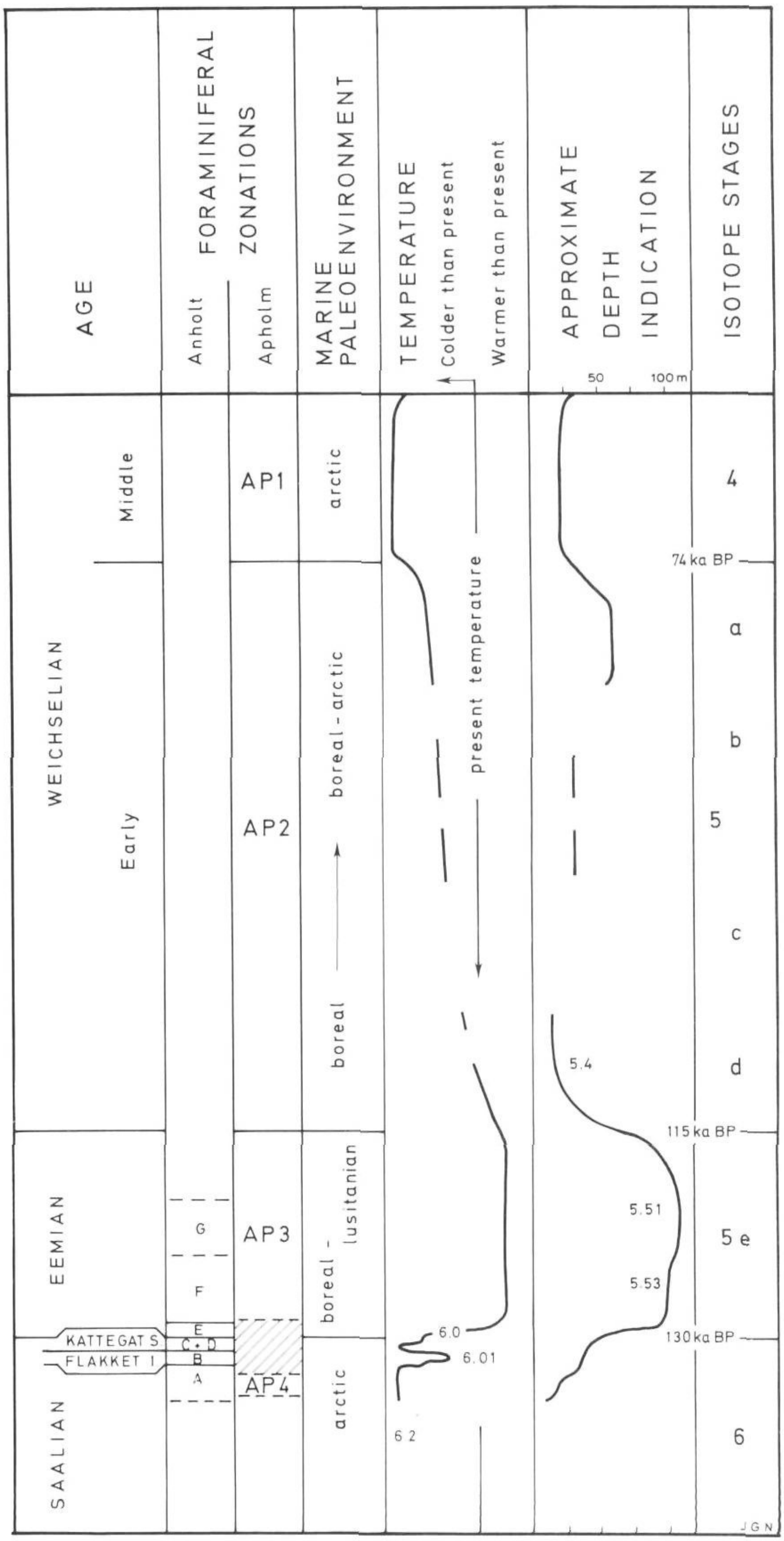

FIGURE 7. Changes in temperature and water depth during the Saalian, Eemian and Early Weichselian indicated by foraminifera in borings from northern Denmark (after Knudsen and Lykke-Andersen, 1982; Knudsen, 1984, 1992; Lykke-Andersen and Knudsen, 1991; Seidenkrantz, 1993a), and correlation to specific isotope events of Pisias *et al.* (1984) and Martinson *et al.* (1987). Hatched area represents a hiatus.

Courbes des changements des températures et de la profondeur de l'eau pendant le Saalien, l'Eémien et le Weichselien inférieur, tels que reconstituées à partir des assemblages des foraminifères issus des forages du nord du Danemark (selon Knudsen et Lykke-Andersen, 1982; Knudsen, 1984, 1992; Lykke-Andersen et Knudsen, 1991; Seidenkrantz, 1993a), et corrélations avec quelques événements isotopiques (voir Pisias et al., *1984; Martinson* et al., *1987). La zone hachurée représente une lacune.*

THE EEMIAN/WEICHSELIAN BOUNDARY (SUBSTAGE 5e/5d)

The disappearance of deeper water species and a distinct increase in frequency of shallow water Elphidiidae above the Eemian/Weichselian boundary in the Apholm boring indicate that the gradual decrease in water depth in the Late Eemian was followed by a major drop in sea level at the Eemian-Weichselian boundary (Fig. 7) (Knudsen, 1984). This sea level drop occurred within a time span of no more than 3000 years (Knudsen, 1992).

A similar sea level drop was reported by Zagwijn (1977, 1983) in the southern North Sea region and it presumably corresponds to the rapid, and major, increase in $\delta^{18}O$ that spans the interval from just after isotope event 5.51 to event 5.4 (Martinson *et al.*, 1987). This corresponds to the transition between isotope substages 5e and 5d. The magnitude of this sea level drop (60-70 m) furthermore coincides with the major drop in sea level documented in the Huon sea level record during the same period (see Chappell and Shackleton, 1986).

Lowermost part of the Early Weichselian in the Apholm boring is characterized by the boreal-lusitanian species *E. excavatum*, forma *selseyensis* and other boreal shallow water taxa. The arctic *clavata* form of this species gradually replaces forma *selseyensis* during the Early Weichselian. Simultaneously there is a marked increase in the frequency of the arctic species *C. reniforme*. This change in the foraminiferal assemblages illustrates a gradual and delayed cooling of the water masses compared to the sea level drop, a phenomenon which has also been observed in the deep sea stable isotope record (Duplessy and Shackleton, 1985). True arctic glacial conditions were presumably not attained until the beginning of isotope stage 4 (Fig. 7).

EEMIAN PALEOOCEANOGRAPHY

The foraminiferal faunas living in the Kattegat and Skagerrak today (Conradsen *et al.*, 1993) belong to the boreal faunal province (Figs. 5, 6a) and several of the lusitanian species recognized in Eemian sediments in the area (*e.g.*, *S. subspinescens* and *Q. padana*) do not live in this area today. This indicates that the water temperatures during the last Interglacial must have been somewhat higher than at present. Similar high water temperatures, at least 2-3°C higher than at present, are also indicated by faunas from outcrops and borings in the eastern North Atlantic region (Voorthuysen, 1957; Mangerud *et al.*, 1981; Sejrup, 1987; Penney, 1989; Knudsen, 1985b, 1988; Sejrup and Larsen, 1991). This indicates a northward migration of faunal provinces (Sejrup, in prep.) and the penetration of a warmer water mass into the North Sea area during the Eemian. A strengthened North Atlantic Current presumably allowed its influence to extend further north and warm lusitanian water to pass around northern Scotland and into the North Sea (Fig. 6a,b) (Knudsen, 1992; Sejrup and Knudsen, 1993).

The relatively abrupt decline in water temperature, which resulted in the change from a lusitanian to a boreal environment at the Eemian/Weichselian boundary and a southward displacement of the faunal provinces (Knudsen, 1992), was presumably caused by a corresponding weakening of the North Atlantic Current. The Late Eemian sea level drop, however, indicates that the initial formation of ice sheets occurred prior to the change in the circulation pattern in the surface currents in the Northeastern Atlantic Ocean at the stage 5e/5d boundary.

SUMMARY

The last Interglacial in Northwest Europe (the Eemian Interglacial) corresponds to stable isotope stage 5e and covers a time period of approximately 15,000 years (*ca.* 130-115 ka). Despite the relatively short time range, remarkably thick, marine, interglacial sequences (up to 60 m) have been recorded in borings from shelf areas in northern Denmark. These thick sequences allow high resolution studies of the Eemian Interglacial in the area.

Data from borings in northeast Denmark indicate that the environmental change from the glacial conditions of stable isotope stage 6 (Saalian) to the interglacial of substage 5e (Eemian) occurred gradually over a period of a few thousand years. The transition was interrupted by a short term cold spell, the "Kattegat Stadial", the equivalent of the Younger Dryas cold spell at the Weichselian-Holocene transition.

The Saalian-Eemian transition in Northwest Europe was characterized by a major warming to temperatures a few degrees higher than today coinciding with an initial sea level rise of about 50-60 m. At the same time a strengthening of the North Atlantic Current caused a northward migration of marine faunal provinces.

Records from borings and outcrops in Denmark and northern Germany suggest a possible further rise in sea level during the Middle Eemian. The Late Eemian, however, experienced a distinct sea level drop of about 15 m, which may indicate the expansion of ice caps as early as in the upper part of substage 5e. The foraminiferal faunas, however, reveal no decrease in water temperature below the Eemian/Weichselian (substage 5e/5d) boundary.

In northern Denmark the sea level drop during the Late Eemian resulted in a decrease in water depth of about 60-70 m at the Eemian/Weichselian (stage 5e/5d) boundary. This sea level drop, which accompanied a climatic change in the area from boreal-lusitanian to boreal conditions, occurred over a time period of about 3000 years. The final temperature drop to arctic, true glacial conditions occurred at the Early-Middle Weichselian transition (stage 5/4).

ACKNOWLEDGEMENTS

We express our gratitude to David N. Penney and the journal reviewers for critically reading the manuscript and to Jette Gissel Nielsen for preparing the illustrations. We also thank David N. Penney and Hans Dieter Zimmermann for correcting the English and German of the text, respectively, and Martine Lapointe and Anne de Vernal for translating the Frensh abstract and figure captions.

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