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QUATERNARY POLLEN BIOSTRATIGRAPHY IN THE BRITISH SECTOR OF THE CENTRAL NORTH SEA

Sten Ekman

Department of Geology
GÖTEBORG 1997

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ABSTRACT

Quaternary sediment sequences from the Fladen Ground and the Devil's Hole area in the British sector of the central North Sea are investigated on their pollen content. The sequences are correlated on the basis of pollen biostratigraphy, with reference taken to existing borehole and seismic data.

The Early Pleistocene sediment sequences are correlated with the pollen-based Dutch composite stratigraphy where a good correlation with the geomagnetic polarity time scale exists. Comparisions are drawn between existing palaeoenvironmental reconstructions from marine microfossil data from the sequences and the Dutch pollen stratigraphy. The borehole sequences are interpreted as younger than the Olduvai geomagnetic event as massulae of the freshwater fern *Azolla filiculoides*, a species that did not appear before that event, is present in a reversed polarity sequence. Considerable freshwater influx at the base of the pollen profiles can probably be related to delta progradation from the south during Early Pleistocene times. Indications of glaciofluvial influx in the upper part of this freshwater-influenced interval are correlated with the Menapian stage. An hiatus in the Devil's Hole vicinity separates the Menapian interval from sediment of Bavel Interglacial age. During the earlier phase of the succeeding Linge Glacial strong fluvial discharge at first influenced the Devil's Hole area after which calm arctic to high arctic marine conditions prevailed in a depositional environment influenced by meltwater from the British ice sheet. The pollen data from the later part of the Linge glacial in the Devil's Hole area indicates glaciofluvial influences from the Scandinavian ice sheet.

The most pronounced influence of reworked pre-Quaternary sediments in the Middle Pleistocene sediment sequences is identified in an upper interval, rich in pre-Neogene palynomorphs, and in a lower interval, rich in Neogene palynomorphs. This change can be related to Middle Pleistocene glacial periods. The pollen content in the younger interval indicates a British provenance, possibly correlated with the Saalian stage. The pollen content in the older interval indicates derivation from the Scandinavian ice sheet, and may correlate with the Elsterian stage. The pollen stratigraphies between these two intervals reflect a vegetational transition from dwarf shrub heaths and peatlands towards boreal forests, possibly followed by a return to a more open landscape. This pollen stratigraphical succession is best preserved in the Devil's Hole sequences. In the Fladen Ground the upper part of the sequence may have been glacially eroded. The Devil's Hole sequences are probably underlain by deltaic deposits of the Cromerian Complex and earlier.

Biostratigraphical and AMS ^{14}C core data from Late Weichselian to Early Holocene Devil's Hole area sediment indicate accumulation from c. 15.7 ^{14}C ka BP on an erosional surface on overconsolidated Saalian sediment. When the lower part of the Late Weichselian sediment accumulated the area was c. 40 m lower than present. This interpretation is based on two assumptions; 1) that the sediment is now about 20 m above that of global sea level at the time of deposition and 2), that the marine microfaunal content reflects a water depth of about 20 m at that time. Crustal downflexure caused by Late Weichselian glacial loading of the core area is considered as the most plausible explanation. Indications of a regressional minimum within Late Weichselian marine microfaunas c. 12 ^{14}C ka BP in age probably reflects local isostatic rebound exceeding global eustatic rise.

Keywords: *Bavelian, biostratigraphy, Cromerian Complex, delta sediment, Elsterian, glacial isostasy, glaciomarine sediment, Late Weichselian, Menapian, North Sea, Pleistocene, pollen, Saalian, stage 7.*

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The most pronounced influence of reworked pre-Quaternary sediments in the Middle Pleistocene sediment sequences is identified in an upper interval, rich in pre-Neogene palynomorphs, and in a lower interval, rich in Neogene palynomorphs. This change can be related to Middle Pleistocene glacial periods. The pollen content in the younger interval indicates a British provenance, possibly correlated with the Saalian stage. The pollen content in the older interval indicates derivation from the Scandinavian ice sheet, and may correlate with the Elsterian stage. The pollen stratigraphies between these two intervals reflect a vegetational transition from dwarf shrub heaths and peatlands towards boreal forests, possibly followed by a return to a more open landscape. This pollen stratigraphical succession is best preserved in the Devil's Hole sequences. In the Fladen Ground the upper part of the sequence may have been glacially eroded. The Devil's Hole sequences are probably underlain by deltaic deposits of the Cromerian Complex and earlier.

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INTRODUCTION

Stratigraphical information from the North Sea basin is important for understanding the palaeoenvironmental development of northwestern Europe. Besides unravelling the evolution of this epeiric sea itself, these data can provide links between onshore stratigraphies in the UK and continental northwestern Europe and between these onshore records and more complete, but condensed, deep ocean records (Long *et al.*, 1988; Gibbard *et al.*, 1991; Funnell, 1995). The understanding of such correlations between continental and marine records is crucial for achieving a comprehensive view of Global changes (Veldkamp and van der Berg, 1993).

For the correlation of onshore and offshore stratigraphies, pollen analysis can be a useful tool because: 1) pollen and spores derived from terrestrial vegetation are the most common microfossils occurring in both continental and ocean sediments (Mudie, 1982) and, 2) several studies from various marine settings have demonstrated a close correspondence between pollen assemblages from modern continental margin sediments and vegetation zones onshore (e.g. Muller, 1959; Hooghiemstra, 1988; Heusser, 1988; Mudie and McCarthy, 1994).

Pollen assemblages in the North Sea are of mixed origin and call for careful interpretion because of reworking, mainly by glaciers, and transport by water from widely differing regions and river systems. Nevertheless, palynological data from Quaternary North Sea sediments can be used to make palaeoenvironmental interpretations and stratigraphical correlations. In the present study, Quaternary sedimentary sequences from the British sector of the central North Sea (Fig. 1) have been analysed for their pollen content and subsequently correlated with onshore sequences, in particular the pollen-based Dutch composite stratigraphy (cf. Zagwijn, 1985; De Jong, 1988). Comparisons are drawn between palaeoenvironmental reconstructions from the onshore sequences and palaeoenvironmental reconstructions from the North Sea sequences, which are based on pollen in addition to marine microfossil data.

The dissertation is based upon the following six papers:

I. Ekman, S.R. 1995. Late Weichselian to early Holocene litho- and biostratigraphy in the Devil's Hole area, central North Sea, and its relation to glacial isostasy. *Journal of Quaternary Science, 10.* 343-352.

II. Ekman, S.R. and Scourse, J.D. 1993. Early and Middle Pleistocene pollen stratigraphy from British Geological Survey borehole 81/26, Fladen Ground, central North Sea. *Review of Palaeobotany and Palynology, 79,* 285-295.

III. Ekman, S.R. 1994. Early and Middle Pleistocene pollen stratigraphy from British Geological Survey borehole 81/29, Devils Hole area, central North Sea. *Netherlands Journal of Sea Research, 32,* 49-62.

IV. Ekman, S.R. 1997. Pleistocene pollen stratigraphy from borehole 81/34, Devil's Hole area, central North Sea. Manuscript accepted for publication in *Quaternary Science Reviews.*

V. Ekman, S.R. 1997. Middle Pleistocene pollen biostratigraphy in the central North Sea. Manuscript (submitted).

VI. Ekman, S.R. 1997. Early Pleistocene pollen biostratigraphy in the central North Sea. Manuscript (submitted).

Reference to the papers are made by using roman numericals, which also apply to the papers as appendixes. Paper I, II and III are reprinted by the permission of Elsevier

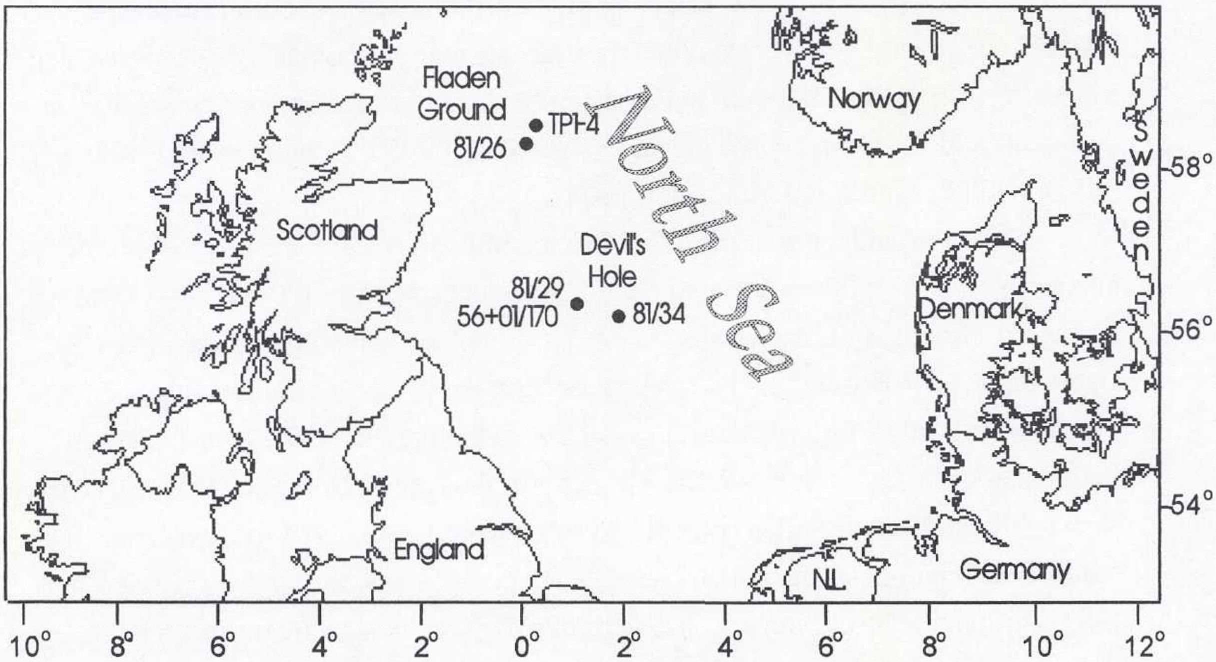

Fig. 1. Sampling sites of investigated borehole sequences

Science Publishers B.V., Netherlands Institute for Sea Research and John Wiley & Sons Ltd, respectively.

Paper I concentrates on the relation between the biostratigraphy of a vibrocore from the Devil's Hole area and Late Weichselian glacial isostasy. Papers II, III and IV provide detailed descriptions of the pollen content of Early and Middle Pleistocene sediment from BGS boreholes 81/26, 81/29 and 81/34 respectively. Papers V and VI provide reviews of the pollen stratigraphies of Middle and Early Pleistocene central North Sea sequences and propose models over the palaeoenvironmental development in the central North Sea.

In addition to a short summary of the six papers on which this thesis is based, I will here give a general view of the development of the North Sea Basin and discuss the usefulness of pollen studies in the marine environment. This will serve as a background for readers not familiar with the area, and will facilitate the understanding of the complexities discussed in the individual papers.

MODERN BATHYMETRY AND OCEANOGRAPHY IN THE NORTH SEA

The North Sea is an epeiric sea between the British Isles and Continental Europe extending approximately from 51° N to 62° N and from 4° W to 12° E (Fig. 1). The shelf edge between Scotland and Norway provides the northernmost limit of the North Sea where it meets the North Atlantic and in the south the English Channel connects with the North Sea. The definition of the central North Sea used here is the area between 56° N and 58° N (c.f. Stoker *et al.*, 1985). The investigated and discussed Fladen Ground borehole sites are considered part of this area, even if their exact positions are just north of 58° N.

The water depth in the North Sea is at maximum c. 50 m south of c. 54° N, i.e. south of the Dogger Bank (Moodley and van Weering, 1993). North of the Dogger Bank (i.e. north of c. 56° N), the North Sea deepens successively to about 180 m at the shelf edge north of Scotland (McCave *et al.*, 1977). The deepest part of the North Sea (750 m), however, is along the southern and southwestern Norwegian Coast, where the Skagerrak and the Norwegian Channel together form an elongated (c. 900 km) and rather narrow (80-90 km) basin (Van Weering, 1981).

Large seasonal temperature variations and a lack of seasonal stratification characterises the southern North Sea. In the central and northern North Sea seasonal stratification is present and in the northern North Sea the bottom temperatures and salinities reflect that of the Atlantic water in the Norwegian Sea (Sejrup and Knudsen, 1993).

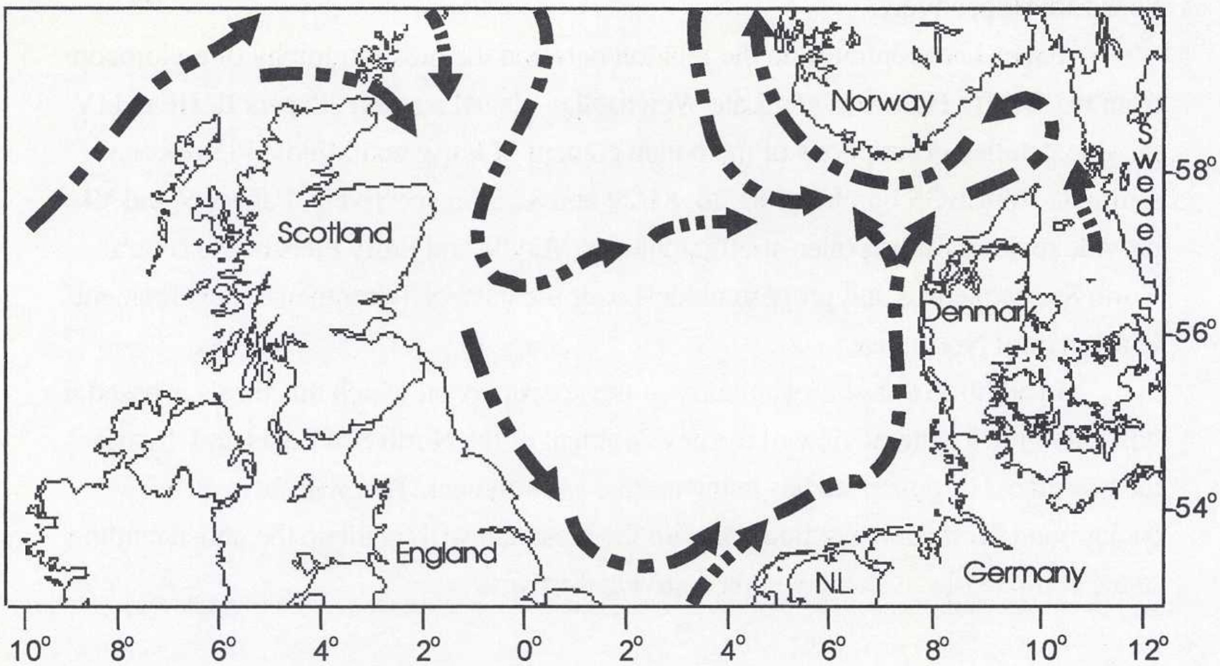

Fig. 2. Present circulation pattern in the North Sea (for references see text)

The North Sea is intermediate between seas with a circulation mainly determined by internal dynamics (e.g. the Mediterranean) and coastal regions of the open sea (cf. Sverdrup *et al.*, 1942). A dominant feature in the dynamics of the modern North Sea is tidal motion (Otto *et al.*, 1990). Where tidal flow is weak as is generally the case north of 54° N, wind stress is an important factor (Eisma and Kalf, 1987). The dominating residual circulation pattern in the North Sea is anticlockwise and the North Sea functions as a mixing-bowl of fresh and oceanic water (Otto *et al.*, 1990). A strong southward flux of warm and saline Atlantic waters enters the northern North Sea (Fig. 2) along: 1) the western slope of the Norwegian Channel, 2) along the western part of the basin east of the Shetland Isles and, 3) mixed with coastal waters along eastern Scotland (cf. Svendsen *et al.*, 1991). This northern influx provides 90% of the North Sea water budget and additional contributors are the English Channel (c.9%) and the Baltic Sea and river runoff (Otto, 1976).

The residual circulation along the Britsh coast, where a mean southerly flow occurs, is somewhat diffuse compared to that along the continental coast where the northerly current is strong and quite restricted up to the Skagerrak, where it meets the deeper North Atlantic inflow (Otto *et al.*, 1990). The outflow from the North Sea is predominantly northwards along the Norwegian coast, where a mixture of oceanic and continental water is transported by the Norwegian Coastal Current to the Norwegian Sea.

Recent sediment accumulation in the North Sea occurs mainly along the eastern margin of the basin (the Wadden Sea, the German Bight, the Skagerrak, the Kattegat and the Norwegian Channel), i.e. along the principal transport direction of suspended matter (Eisma and Kalf, 1987; de Haas *et al.*, 1996). Of fine-grained sediments presently delivered to the North Sea, 50-70% reaches the Skagerrak (Longva *et al.*, 1996), of which a part is transported as suspended load by the Norwegian Coastal Current to the Norwegian Channel and the Norwegian Sea (de Haas *et al.* 1996). Less than 10% of the organic carbon in recent Skagerrak sediment have a local primary production source (cf. de Haas, 1996).

PRE-QUATERNARY DEVELOPMENT OF THE NORTH SEA BASIN

The creation of the North Sea basin was initiated by a secondary rift system simultaneously with the Mesozoic rifting in the North Atlantic which separated Europe from North America (Ziegler and Louwerens, 1977). Isostatic adjustment to sediment loading and stretching events during the rifting were the main reasons for the subsidence of the North Sea area from Early Cretaceous time onward (cf. Kooi *et al.*, 1991). This subsidence formed a sedimentary basin which had approximately the same areal extent as that of North Sea today. The floor of the intial sedimentary basin is now at a maximum depth of about 3500 m along the former rift zone (cf. Veenstra, 1970, Gibbard, 1988).

The North Sea subsidence was interrupted during mid-Miocene times by regional stresses generated by continental convergence of the Alpine orogeny (Glennie, 1990), also responsible for creating the template for the modern drainage pattern in North West Europe (cf. Gibbard, 1988). Subsequent relaxation of this stress system allowed subsidence to proceed and, in turn, the development of one of the worlds major delta systems in the southern part of the North Sea basin between late Miocene (c. 10 Ma) and late mid-Pleistocene times (Zagwijn, 1989; Cameron *et al*, 1993b). The resultant sedimentary infill is shallow marine (littoral and epineritic) and continental (coastal plain and deltaic) in character (Zagwijn, 1989).

North Sea depocentres during the Neogene were in marine nearshore environments proximal to the growing deltas (Zagwijn, 1989). Probably due to rapid tectonic subsidence of the German Bight and Ringköping-Fyn High the Miocene deltaic deposits are primarily restricted to the German and Danish sectors of the North Sea (Cameron *et al.*, 1993a). An extensive delta developed in that area at the mouth of an ancient river system which drained the Baltic region and the northern lowlands of Northwest Europe until the Menapian (Bijslma, 1981; Gibbard, 1988). The Miocene delta construction in the eastern part of the North Sea basin caused considerable expansion of coastal lowland area and widespread peat formation, which now is reflected by huge deposits of Miocene brown coal and brown coal sands (Gibbard, 1988; Zagwijn, 1989). The thickest Pliocene deltaic deposits are found in the central Dutch sector of the North Sea (Cameron *et al.*, 1993) related to continuous growth of the delta from the proto river Rhine (Zagwijn, 1989).

QUATERNARY DEVELOPMENT IN THE NORTH SEA REGION

While the overall development of the North Sea basin during the Tertiary is characterised by subsidence rates more or less in accordance with the post-rift development of rifted continental margins (Sclater and Christie, 1980), a unusually rapid sedimentation characterises the Quaternary (Kooi *et al.*, 1991). This results in Quaternary sediment thicknesses locally up to 1000 m along the former rift zone (Caston, 1977). This indicates an extremely high rate of local subsidence, about ten times the mean Tertiary rate, possibly due to stress changes associated with North Atlantic plate reorganisation (Cloething *et al.*, 1990).

Biostratigraphical divisions of the Quaternary are based on the result of interpreted environmental changes since the short duration of the Quaternary hampers biozonations based on the appearance and extinction of species (cf. Shotton, 1973). As the Quaternary is characterised by an oscillating climate, climatic fluctuation has provided the most suitable basis for its subdivision and the definition of various (climatic) stages. The most complete records of these fluctuations are oxygene isotope stratigraphies from deep-sea cores (e.g. Shackleton *et al.*, 1991). However, the deep-sea record is normally very condensed, giving poor temporal resolution. More detailed records, although representing shorter time periods and bounded by unconformities, are present in terrestrial and shelf environments. Of the onshore records in northwestern Europe the most complete stratigraphy over the cyclic fluctuations between warm temperate (interglacial) and cold climatic conditions, is the palaeobotanical record from the Netherlands on the southeastern margin of the North Sea (Fig. 3, e.g. Zagwijn, 1985, 1989; De Jong, 1988). The most complete British onshore stratigraphy is compiled from East Anglian sequences on the southwestern margin of the southern North Sea (e.g. West, 1961, 1980). The correlation between the UK and Dutch stratigraphies is not completely satisfactory but it is clear that the East Anglian stratigraphy is discontinuous in comparision with the Dutch composite stratigraphy, and lacks records covering the interval from c. 1.7 to 0.6 Ma (cf. Gibbard, 1991; Funnell, 1995, 1996). One possible reason for this is that the British side of the southern North Sea has been an area of net uplift during the Pleistocene (Boulton, 1992; Bridgland and D´Olier, 1995) in contrast to the progressive isostatic downwarping along the former rift zone extending from the North Sea into the Netherlands.

It is common practice in Northwest European stratigraphic work (cf. Van Voorthuysen *et al.*, 1972; Zagwijn, 1989) to place the Quaternary-Tertiary boundary at the point of the first arrival of cold conditions (Praetiglian in the Dutch stratigraphy) somewhat after the boundary between the Matuyama and Gauss geomagnetic epochs (c. 2.6 Ma, Valet and Meynadier, 1993). Associated with the deforested and permafrost conditions during the Praetiglian and succeeding Early Pleistocene cold stages is the extinction of 'Tertiary-relict' plant taxa (Zagwijn, 1960; Van der Hammen, 1971; West, 1980). The younger age for the Plio-Pleistocene boundary, just below the top of the Olduvai geomagnetic event at c. 1.8 Ma (Hilgen, 1991), given in a later redefinition (cf. Aguirre and Pasini, 1985) is not applied here. The lowermost Pleistocene sediment in the central North Sea is affected by salt movement and faulting (Gatliff *et al.*, 1994).

From marine sediments of Tiglian age (c. 2.4-1.7 Ma), from the southern North Sea (Cameron *et al.*, 1984) and East Anglia (Zalasiewicz *et al.*, 1991), palaeoclimatic signals of various microfossil groups are in conflict. The pollen assemblages indicate oceanic grass heath, herbaceous communities of open habitats, park tundra and boreal forest, similar to those of British Early Pleistocene cold stages. Lithological, palaeomagnetic and malacological data are consistent with such a correlation (Zalasiewicz *et al.*, 1991). In contrast, foraminiferal assemblages indicate temperate conditions, and dinocyst assemblages warm-temperate to subtropical conditions. Inferred explanations include: a) reduced forest cover due to leaching and impoverishment of soils (Cameron *et al.*, 1984), b) reduced forest cover due to increased drought or seasonality of rainfall (Zalasiewicz *et al.*, 1991), c) mixing of pollen of different provenance and redeposition offshore (Long *et al.*, 1988), d) a much slower response to climatic deterioration of the North Sea during the Early Pleistocene compared to the Late Pleistocene (Zalasiewicz *et al.*, 1991), e) non-deposition during maximum climatic deterioration due to marine regression (Cameron *et al.*, 1984), f) Atlantic water masses flowing much farther north in the Early Pleistocene than now (Cameron *et al.*, 1984; Zalasiewicz *et al.*, 1991). A more marked gradient of oceanity/continentality across Europe during the Tiglian than presently, indicated by pollen (West, 1961), may reflect a such warm temperate water mass at British latitudes (Cameron *et al.*, 1984). Reported from East Anglian sites are

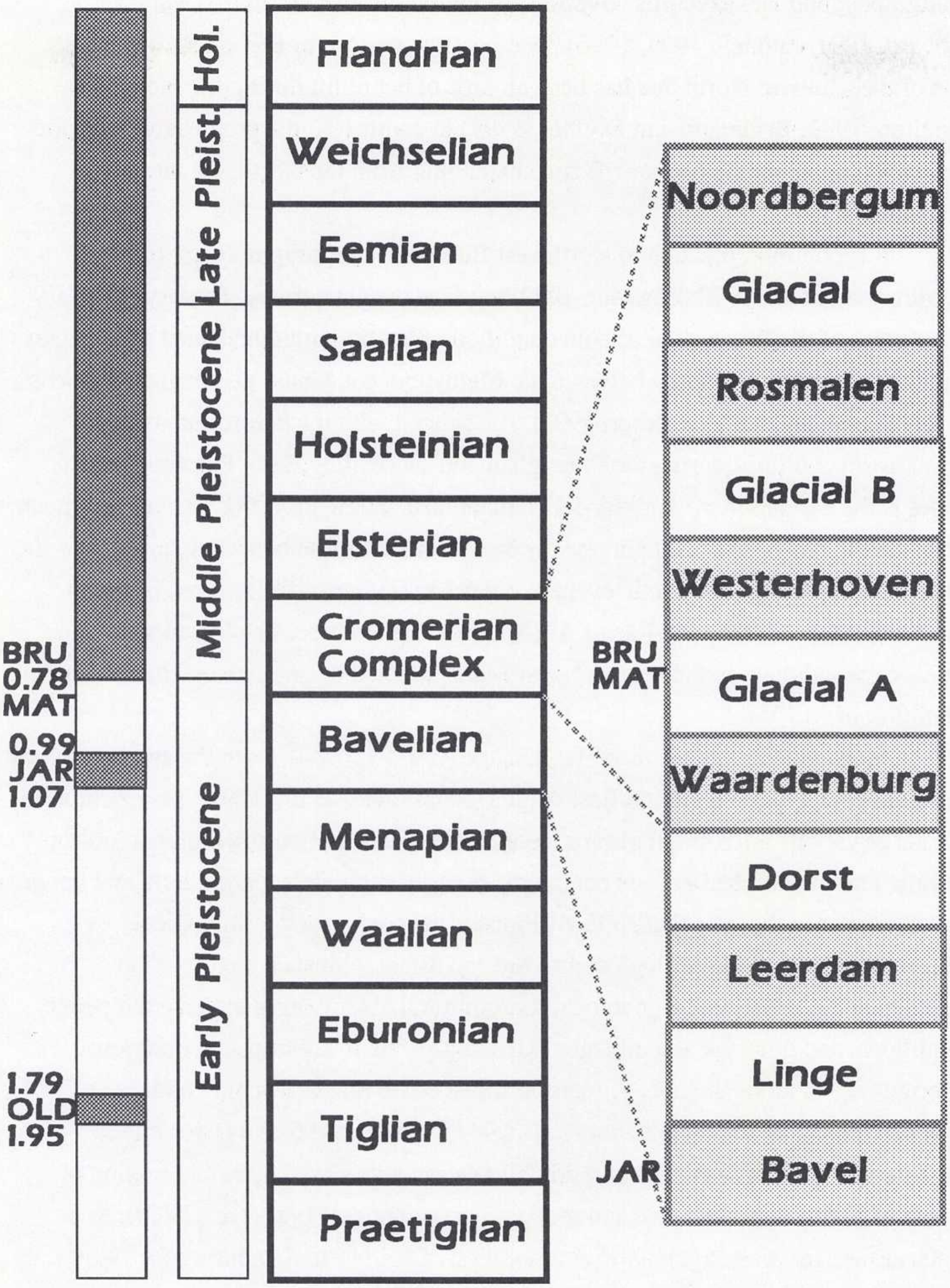

Fig. 3. The pollen-based Quaternary stratigraphy from the Netherlands and its relation to the palaeomagnetic time scale (not to scale). Age in Ma. Hol = Holocene, Bru = Bruhnes, Mat = Matuyama, Jar = Jaramillo, Old = Olduvai.

additionally marine sediments of (late) Tiglian age from which foraminiferal assemblages agree with pollen assemblages in indicating cold conditions (cf. West *et al.*, 1980).

During the Eburonian (c. 1.7 Ma) or somewhat earlier, the coalescence of deltas from the Rhine, Meuse, Scheldt and the comparatively minor British rivers caused a swing of delta advance, from west or south-west to a north-westerly direction (cf. Zagwijn, 1979; Cameron *et al.*, 1993a; Gatliff, *et al.*, 1994). Climatic fluctuation appears not to have been a dominating controlling factor of the growth of this single delta-system (cf. Gatliff *et al.*, 1994).

Pronounced southern withdrawal of vegetation belts during cold stages occurred from the Menapian (c. 1.15 Ma, cf. Funnell, 1996) onward, reflected in Dutch pollen profiles by successive immigration of tree taxa in the following temperate stages (De Jong, 1988). This indicates considerably more severe climate during the cold stages from the Menapian onward. In agreement with this are lithological studies of the 'Complex of Hattem' in the Netherlands (Lüttig and Maarleveld, 1961; Zandstra, 1971, 1983) which indicate that NW European glaciations of regional extent appeared during the Menapian (Bijlsma, 1981), probably for the first time during the Quaternary. During this Early Pleistocene stage and following Bavelian and Cromerian Complex glacial stages, some marginal sediment source areas of the North Sea basin became glaciated (e.g. Ruegg and Zandstra, 1977; Gibbard; 1988; Boulton, 1992) and at some time(s) also parts of the North Sea basin (cf. Stoker and Bent, 1985; Sejrup *et al.*, 1987, 1994). These glaciers reaching the shelf were not able to hinder deposition of sediments in the North Sea delta, however (Gatliff *et al.*, 1994). During the Bavelian, the strong 100 000 year cycle of glacials and interglacials was initiated (cf. Boulton, 1992; Funnell, 1995).

Almost the whole North Sea basin south of 56^{o} N had developed into a wetland complex of delta top sediment in early Cromerian Complex times (Gatliff *et al.*, 1994). This fluvio-deltaic plain is named Ur-Frisia (Cameron *et al.*, 1992) and the delta top lithofacies is strongly diachronous, from Tiglian in age in the south to Cromerian Complex in age in the north (Cameron *et al.*, 1992; Funnell, 1995). The rivers Thames and Rhine probably coalesced to the same river valley on the (Ur-Frisia) fluvio-deltaic plain (Bridgland and D´Olier,1995), which ranked in size with the modern Ganges/Brahmaputra, Mekong and Yangtse-Kiang deltas (Cameron *et al.*, 1993a). It is considered a major silt source for loess deposits present in adjoining areas onshore (Gibbard, 1988).

Reduction of fluvial sediment input during the Cromerian Complex caused decay of the delta (Gibbard, 1988; Cameron *et al.*, 1993a). Widespread invasions of ice across the basin itself occurred during the following Elsterian (Anglian in the UK), Saalian (Wolstonian) and Weichselian (Devensian) glacial stages. Intervals of marine transgressions over the former delta plain and the development of strongly tidal marine conditions similar to the modern occurred between the glacials (cf. Cameron *et al.*, 1993a,b).

There are currently different opinions as to whether the Elsterian glacial stage (as well as the Anglian stage, cf. Boulton, 1992) correlates with stage 8 (e.g., Linke *et al.*, 1985; Sejrup and Knudsen, 1993), stage 10 (e.g., de Jong, J.; 1988; Veldkamp and van der Berg, 1993) or stage 12 (e.g., Rousseau *et al.*; 1992; Funnell, 1995) in the $\delta^{18}O$ stage scale. The British and Scandinavian ice sheets are interpreted to have coalesced during the Elsterian stage due to an advance of the latter ice across the North Sea basin which ultimately stopped growth of the already decaying delta (Gibbard, 1988, 1995). As a consequence northward river drainage into the North Atlantic was blocked and a large ice-dammed lake developed in the southern North Sea and in adjacent areas of the Netherlands and Germany; eventual catastrophic discharge of this lake into the English Channel, due to breaching of the Weald-Artois anticline, has been proposed as a mechanism for the formation of the Strait of Dover (Gibbard, 1988, 1995; Smith, 1992).

The sculpturing of the onshore landscape by the Elsterian ice was fundamentally different from that of subsequent glaciations and in southern ice marginal areas it is characterised by a net-like system of deep channels (Ehlers *et al.*, 1984). Features such as ice-pushed ridges, tongue-shaped basins, lodgement tills and glacially transported erratics are in the lowlands of Northwest Europe scarse or absent from the Elsterian but rather common during the subsequent glaciations (Zagwijn, 1989).

Major incisions similar to the Elsterian channels onshore are present in the North Sea. Based on seismic studies, three major incision episodes are distinguished (Holmes, 1977), of which the oldest was the most significant (Cameron *et al.*, 1987). These episodes have been correlated with the Elsterian, Saalian and Weichselian (Stoker *et al.*, 1985). The incisions are boat-shaped in plan, with an irregular thalweg (e.g. Gatliff *et al.*, 1994) and usually considered to have been formed by glacial processes, such as subglacial meltwater under pressure (Boulton and Hindmarsh, 1987) or jõkulhlaup (Wingfield, 1990). Because of their shape, the term 'scaphiform' has been proposed as a descriptive nongenetic term (Cameron *et al.*, 1992).

The maximum glacial extent of the Saalian ice in the North Sea and British Isles are poorly known and there is active debate whether the British and Scandinavian ices coalesced (Gibbard, 1988, 1995) or not (Cameron *et al.*, 1993b). A colourful debate concerning the maximum glacial extension in the North Sea during the Weichselian stage (cf. paper I), based mainly on the distribution of major incisions, glacial diamiction and ice pushed ridges but also shore displacement curves, is also currently active (cf.; Ehlers and Wingfield, 1991; Cameron *et al*, 1993b; Lambeck, 1993; Sejrup *et al.*, 1994).

SEISMOSTRATIGRAPHICAL FORMATIONS

The investigated sequences form four seismostratigraphical formations (Stoker *et al.*, 1985), the Aberdeen Ground, Ling Bank, Fisher and Forth formations (Fig. 4).

Different stratigraphies have been established to the north and south of 56^{o} N in the British sector of the North Sea and full integration between them has yet to be achieved (cf. Gatliff *et al.*, 1994). The deltaic sediments north of 56^{o} N are grouped into the Aberdeen Ground Formation in contrast to south of 56^{o} N where the deltaic sequence is subdivided into several formations. This because of increasing difficulties basinwards to recognise individual deltaic formations in seismic profiles (Gatliff *et al.*, 1994). The Early and Middle Pleistocene Aberdeen Ground Formation is the oldest defined Quaternary formation in the British sector of the central North Sea where it forms a wedge-shaped unit thinning markedly to the west but is at least 130 m thick in the Devil's Hole area (Stoker *et al.*, 1985). In that area the formation is interpreted to have accumulated in a delta front setting, periodically as rapid deceleration of argillaceous silts and silty fine sands (possibly during hypopycnal flow) and periodically as mud deposition from suspension in a lower energy environment (Stoker and Bent, 1987). In the Fladen Ground, the formation predominantly accumulated as sublittoral muds in a broad marine basin and additionally contains glacigenic sediments (Sejrup *et al.*, 1987; Andrews *et al.*, 1990). The boundary between the Bruhnes and Matuyama geomagnetic epochs (c. 0.78 Ma, Valet and Meynadier, 1993), i.e. the Early-Middle Pleistocene boundary, as well as the Jaramillo geomagnetic event (c. 0.99-1.07 Ma), have been recognised in the Aberdeen Ground Formation (Stoker *et al.*, 1983; Sejrup *et al.*, 1987).

The maximum thickness of the Ling Bank Formation is about 100 m where it infills deep erosive features. The erosion surface at the base of this Middle Pleistocene unit is highly irregular in the northern part and comparatively planar in the southern part of the British sector of the central North Sea (Stoker *et al.*, 1985). Sediment from this formation has been recovered in a few boreholes.

The Fisher Formation is up to 90 m thick in the eastern part of the British sector of the central North Sea but generally does not exceed 6 m in thickness and occurs rarely in the western part (Gatliff, 1994). This formation is interpreted as Saalian in age and occurs above a planar erosion surface which cuts across the Ling

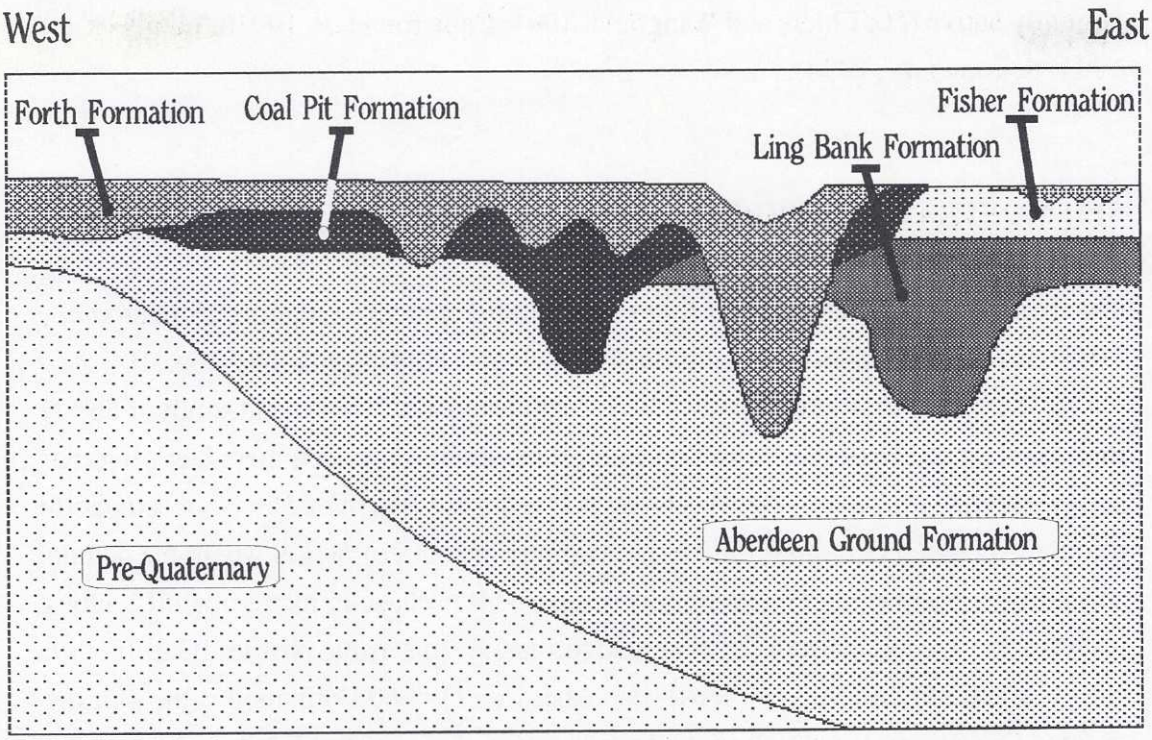

Fig. 4. Schematic section illustrating the relationships of seismostratigraphical formations in the British sector of the central North Sea in a transect from West to East. Horizontal distance c. 100 km. Total sediment thickness c. 250 m.

Bank and Aberdeen Ground formations. The top of the unit is generally more irregular and associated erosional features are usually infilled by sediment of the Coal Pit Formation and the Forth Formation. The Coal Pit Formation, which is Middle and Late Pleistocene in age, is not represented in the investigated cores.

The Forth Formation crops out over most of the British sector of the central North Sea where it forms the uppermost Quaternary unit. This unit is usually not more than 20 m thick although the maximum thickness exceeds 150 m in deep erosive features in the Devil's Hole area (Stoker *et al.*, 1985; Gatliff *et al.*, 1994). The formation is interpreted as Late Weichselian to early Holocene in age.

POLLEN AND SPORE TAPHONOMY IN THE MARINE ENVIRONMENT

It is essential to identify the main pathways by which pollen and terrestrial spores reach marine depositional sites. Based on such a description, temporal variations in marine pollen assemblages related to changes in terrestrial vegetation composition can be distinguished from those related to sedimentary pathways, e.g., river drainage and current directions (Mudie, 1982). During transport, pollen grains and spores behave in principal as part of the fine silt and clay fraction. As a result, their distribution in sediment becomes facies dependent, although water and air may sort some taxa selectively by size or density (e.g. Cameron *et al.*, 1983). One way to identify potentially important sources of pollen and spore input to the North Sea is therefore to define the main processes by which silt and clay are supplied to the area.

According to mud budgets constructed for the North Sea (McCave, 1973; Eisma and Kalf, 1979, 1987), the most important sources at present are:

- the North Atlantic, the English Channel, and the Baltic Sea.
- large rivers, of which the Rhine is the most important
- sea floor erosion
- atmospheric fall-out
- the erosion of non-resistant muddy cliffs.
- marine organic production (i.e., irrelevant considering the input of terrestrial pollen and spores and freshwater algae)

The connection of the North Sea with the English Channel did not exist during most of the Pleistocene. Prior to the latest transgression of the Strait of Dover in the early Holocene (cf. Jelgersma, 1979), the Southern Bight of the North Sea was a quiet, shallow embayment of low tidal amplitude; following transgression it attained the present state of strong tidal action with a mean amplitude of 2 m (cf. Scourse and Austin, 1995). Since this transgression, non-depositional conditions have been prevalent in most of the southern and central North Sea. The transfer of energy between the English Channel and the North Sea increases the erosional rate of the sea floor (cf. Eisma and Kalf, 1987) and is important for the circulation pattern in the North Sea which forces mud to pass through and off the southern part to enter the Jutland Current (Erlenkeuser and Pederstad, 1984). This situation is unrepresentative for most of the Cenozoic, since huge amounts of argillaceous Cenozoic sediments of various ages are present in the basin since the Miocene (although considerable hiatus are present also) during which the connection between the North Sea and the English Channel has been very limited (cf. Cameron *et al.*, 1993a,b). Therefore it would be misleading to calibrate Pleistocene pollen stratigraphical investigations against the modern depositional patterns of pollen in the North Sea. During the Pleistocene, the North Sea - English Channel connection may have existed only during the Early and Middle Tiglian and the Eemian, as indicated by malacological data (Meijer and Preece, 1995). This opinion and that of a breach of the Weald-Artois anticline during the

Elsterian (Gibbard, 1988, 1995) are considered not to be mutually exclusive interpretations (Bridgland & D'Olier, 1995; Meijer and Preece, 1995).

Mud transported by inflowing North Atlanctic water masses (predominantly in relatively turbid water above the thermocline) is presumably very poor in pollen, as estimated from other regions (cf. Mudie and McCarthy, 1994).

The influx from the Baltic Sea is presently between Denmark and Sweden into the Skagerrak and further with the Norwegian Current along the Norwegian Channel. Except for periods characterised by extensive glaciations, this path may have been prevalent since the Menapian (when the ancient Baltic River disappeared), which suggests a low input of mud from the Baltic Sea to the British sector of the central North Sea.

According to mud budgets for the North Sea, the present input from erosion of cliffs, e.g., Mesozoic formations along the coast of Yorkshire and parts of southern England and cliffs of till at the coast of Holderness and East Anglia (cf. Pantin, 1991), is considerably lower than the fluvial and aeolian input (McCave, 1973; Eisma and Kalf, 1979, 1987). The eroded coastal cliffs may furthermore be poor in palynomorphs or may only contain pre-Quaternary forms. In a somewhat broader perspective, the erosion by waves, wind, mass movements, tidal processes and ocean currents can not compete with the erosional intensity of regional glaciations. Reworking of sediment during periods characterised by extensive glaciation of the North Sea and adjoining areas is considered responsible for the thick Middle and Late Pleistocene mud deposits in the north and central North Sea (Cameron *et al.*, 1987).

Essential information about pollen-spore taphonomy in marine settings, based on quantitative analyses of pollen-spore distribution patterns in recent marine sediment, has been reported from various regions. The main pathway of the dominant pollen transport to the ocean in most of the studied areas is interpreted to be fluvial discharge from major rivers (cf. Mudie, 1982), since:

- the pollen content in suspended sediment from some large estuaries is more similar to that of the watershed region than that of the shoreline vegetation (cf. Muller, 1959; Groot, 1966).
- *Pinus* pollen is concentrated in plumes on the seabed offshore major rivers (Cross *et al*, 1966; Heusser and Balsam, 1977).
- rivers contains high concentrations of pollen, even in arid regions (Heusser, 1978).
- pollen samplers on ships at sea have captured no or very low numbers of pollen grains (Muller, 1959; Faegri and Iversen, 1964).

However, in regions with a principal offshore wind direction and few large rivers aeolian pollen transport to the ocean can be more important than fluvial transport. This situation pertains along the western North Atlantic coast between c.

38° -55° N (Mudie, 1992; Mudie and McCarthy, 1994) and off Northwest Africa (Melia, 1984; Hooghiemstra, 1988). In the nearshore region (0.1-5 km from the coastline) along the western North Atlantic coast the annual pollen input is estimated to be derived from fluvial ($56*10^{12}$ grains cm^{-2}), aerial ($24*10^{14}$ grains cm^{-2}), marine tides (365 grains cm^{-2}) and recycling (12 grains cm^{-2}) (Mudie and McCarthy, 1994). In this area the pollen-spore concentrations are approximately one order of magnitude lower than corresponding average values for the vegetation formations bordering the coastline (Mudie 1982). Farther offshore (5 km offshore to the shelfbreak), pollen and spore concentrations decrease more gradually with distance from land (Mudie, 1982). The data indicates that pollen-spore abundance decreases offshore exponentially and that annual influx occurs regardless of proximity to large rivers (Mudie, 1982; Mudie and McCarthy, 1994). The input from ice rafting is considered negligible in this region, which is not the case in the Arctic Ocean pack-ice belt, where river runoff is considered the main source of ice-rafted detritus (Mudie and Matthiessen, 1988).

The fresh-water discharge of the Orinoco river, northernmost South America is comparable to that of the combined North Sea/Baltic System in contributing more than 2% of the total world run-off to the ocean, (cf. Baumgartner and Reichel, 1975; Otto *et al.*, 1990). Offshore the Orinoco delta the pollen depositional pattern, as offshore eastern Canada, indicates gradually decreasing pollen concentrations with distance from land (Muller, 1959). Offshore Orinoco, however, the large delta acts as the major pollen transport agency by its discharge of water (Muller, 1959). In sediment from the fluvio-deltaic plain, the pollen assemblages show an over-representation of pollen from local swamp vegetation due to restricted transport facilities. The offshore pollen assemblages, however, are characterised by a uniformly mixed supply (Muller, 1959).

Polymodal pollen distribution patterns are recognised along the NE Pacific coast of US, where as off the Orinoco river, pollen concentrations clearly reflect the influence of fluvial input of pollen (Heusser, 1978; 1988). In the NE Pacific Ocean pollen concentrations are lower on the shelf, higher on the slope and rise and minimal in the basins, indicating pollen bypass of the outer shelf. Nevertheless, continental slope sediments off California contain pollen assemblages reflecting vegetation formations onshore and comprise lower pollen concentrations by a factor of 10 than sediments off the mouths of major rivers, or by a factor of 100 in estuaries and other sedimentary basins onshore (Heusser, 1988).

The calculated modern fluvial input of mud to the North Sea is of greater importance than the aeolian input (McCave, 1973; Eisma and Kalf, 1979, 1987) and it appears most likely that during most of the Quaternary the bulk of pollen and spores was transported to the North Sea by fluvial discharge.

The depositional situation in the North Sea during a large part of the Quaternary is potentially favourable for making correlations between onshore and central North Sea pollen data. The majority of the fluvial pollen load from large rivers settles near the river mouths and during the Cenozoic massive delta expansion occurred in the North Sea (Zagwijn, 1979, 1989). Sediment carried by the Rhine and the Meuse is an essential part of both the deltaic deposits in the North Sea (e.g. Cameron *et al.*, 1993b) and the fluvial deposits in the Graben areas of the Netherlands (Doppert *et al.*, 1975), in which the Dutch composite stratigraphy is based. During the later part of the Early Pleistocene and early part of the Middle Pleistocene the depocentres of the Great European Delta prograded northwards to a position within the central North Sea (cf. Gibbard, 1988; Cameron *et al.*, 1993a; Funnel, 1996). The evidence that pollen assemblages in sediment offshore fluvial outlets is a reflection of the whole catchment area rather than only the shoreline vegetation (cf. Muller, 1959; Groot, 1966) further increases the potential for pollen-based regional marine-terrestrial correlations.

During transport, pollen taxa may be sorted due to different size or density. Identification of these differences in behaviour is of importance when interpreting marine pollen assemblages. For instance, pollen from *Picea* and *Pinus* are well adapted to long-distance transport by wind and water. Their frequency in recent shelf and slope sediments nevertheless reflects that of the main tree species onshore (Mudie and McCarthy, 1984). Both marine distribution patterns (Mudie, 1982) and a positive correlation of pine pollen abundance with precipitation and stream runoff (Heusser, 1988) suggest that *Pinus* are selectively transported seaward particularly in fluvial discharge from large rivers. Poaceae, Cyperaceae, Asteraceae, *Quercus*, *Abies*, *Alnus* and *Betula* tend to decrease abruptly beyond coastal waters and to maintain relatively low, somewhat irregular values on the slope and rise (cf. Mudie, 1982; Heusser, 1988).

During glacial periods, reworked palynomorphs incorporated in glacial and glaciofluvial sediment dominate onshore as well as offshore pollen assemblages. This precludes attempts to evaluate the contemporaneous vegetation. However, the pollen data can help to detect the source of the glacigenic sediment supply. Earlier studies of North Sea sediment have proved that it is possible to make a subdivision of pollen assemblages rich in reworked pre-Quaternary palynomorphs and from that an interpretation of the sediment source (Zagwijn and Veenstra, 1966).

Pollen spectra with high values of pre-Neogene palynomorphs from Quaternary North Sea sediment are considered to reflect a British origin (Zagwijn and Veenstra, 1966). Such spectra are reported from marine sediment from East Anglia (West *et al.*, 1994) and the British sector of the southern (Cameron *et al.*, 1984) as well as the central North Sea (Jansen *et al.*, 1979a; Ekman, 1994). High frequencies of pre-

Neogene forms are also present in glacial sediments with erratic assemblages of British origin exemplified by a diamicton from the Fladen Ground (Sejrup *et al.*, 1987; Ekman & Scourse, 1993) and in boulder clay deposits from the Dogger Bank area (cf. Zagwijn and Veenstra, 1966).

Assemblages with high amounts of Neogene taxa have been attributed to glacial erosion by the Scandinavian ice, e.g. of Miocene Brown Coal Sands in the German Bight (Zagwijn and Veenstra, 1966). In the Netherlands and Northwest Germany fine-grained glacigenic deposits onshore e.g. of the Saalian and the Elsterian are characterised by rather high amounts of reworked Neogene pollen (Van Gijzel *et al.* 1959; Polak, 1963; Menke, 1968; Zagwijn, 1973) while Pre-Neogene palynomorphs are underrepresented (De Jong, 1981).

QUATERNARY POLLEN BIOSTRATIGRAPHY IN THE CENTRAL NORTH SEA - SHORT SUMMARY OF PAPERS

Paper I is a study of Late Weichselian to Early Holocene glaciomarine and marine sediments in a 6-m-long British Geological Survey vibrocore (56+01/170). The sediments are from the Devil's Hole area (Fig. 1) and belong to the Forth Formation (Fig. 4; cf. Stoker *et al.*, 1985). Besides the foraminiferal, pollen and AMS ^{14}C data presented in the study, amino acid (Knudsen and Sejrup, 1993) and ostracod data (Penney, 1990) exist for the core.

The sediment accumulation began c. 15.7 ^{14}C ka BP (extrapolated from the sedimentation rate based on the overlying AMS dates) on an erosional surface on overconsolidated Saalian sediment (cf. Stoker *et al.*, 1985; Jensen and Knudsen, 1988). When the lower part of the core (facies 1) accumulated the core area was c. 40 m lower than present. This interpretation is based on two assumptions; 1) that the sediment is now about 20 m above that of global sea level at the time of deposition (cf. Fairbanks, 1989), and 2), that the marine microfaunal content reflects a water depth of about 20 m at that time (Fig. 5). Crustal downflexure caused by Late Weichselian glacial loading of the core area is considered as the most plausible explanation. Glacial overriding would also explain the overconsolidation of, and the erosional surface on, the underlying Saalian sediment, and the absence of Weichselian sediment older than about 15.7 ^{14}C ka BP at the core site.

Indications of a regressional minimum within the marine microfaunas at 50 cm depth in the vibrocore (just below an unconformity with a minimum age of about 12.1 ^{14}C ka BP) suggest that the Devil's Hole area was glaciated during the

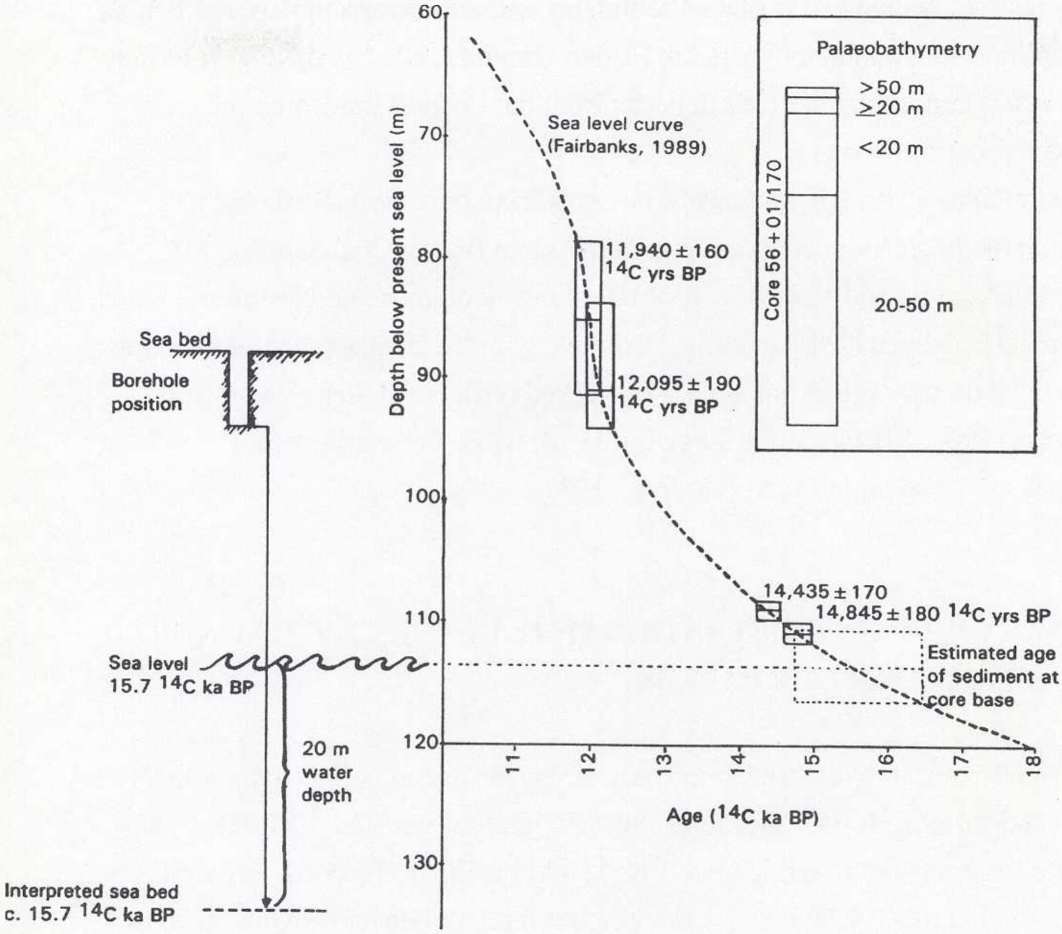

Fig. 5. ^{14}C ages (± 2σ) from core 56+01/170 and the estimated age of its base (15.7 ± 0.9 ^{14}C ka BP) compared with the Barbados sea-level curve (Fairbanks, 1989). The position of the borehole shows that in comparision with the sea-level curve the sediment at core base must have been at least 20 m lower to allow marine sedimentation. In addition, foraminiferal and ostrcod data (in the box) indicate a water depth of approximately 20 m during deposition. Thus, the sea-bed must have been ca. 40 m lower than at present. This is interpreted as an effect of previous glacial loading.

Weichselian (cf. Jansen, 1976; Ehlers and Wingfield, 1991; Cameron *et al.*, 1993b). The fall in sea level at that time probably reflects that local isostatic rebound exceeded the global eustatic rise (cf. Fairbanks, 1989). The uppermost 10 cm of sediment contains an interglacial pollen flora correlated with onshore pollen assemblages from the Boreal Chronozone (sensu Mangerud *et al.*, 1974).

Paper II presents a pollen stratigraphy, subdivided into eight pollen assemblage zones (I-VIII), from the 200 m deep BGS borehole 81/26 from the Fladen

Ground (Figs. 1 and 6). Pollen stratigraphical data support previous interpretations of this core based on a multidisciplinary study (Sejrup *et al.*, 1987), including foraminiferal, chemical and grain-size analysis and amino acid and palaeomagnetic measurements. Pollen zones II to IV, which occur below the Bruhnes/Matuyama boundary are interpreted to correlate with the Bavelian complex and possibly two interglacial stages within that, the Bavel and Leerdam interglacials. A pronounced peak of the Early Pleistocene dinocyst *Habibacysta tectata* (Harland, 1995) in zone II, was erroneously determined as the nymphaeid taxon *Brasenia. Habibacysta tectata* is interpreted to have occurred most abundantly during mild - to cool-temperate conditions (cf. Head, 1994). Pollen zones V to VIII indicate predominantly cold conditions.

Paper III describes the palynomorph content of Early and Middle Pleistocene sediments from the 140 m deep BGS borehole 81/29 from the Devil's Hole area, taken at the same time and site as the vibrocore presented in paper I (Fig. 1). The pollen stratigraphy is subdivided into eight pollen assemblage zones (A-H). The Early Pleistocene sequence in 81/29 is interpreted as predominantly of Bavelian age and is correlated with the pollen stratigraphy from borehole 81/26 (paper II); it also supports a previous foraminiferal correlation (Jensen and Knudsen, 1988). The overlying Middle Pleistocene sequence in 81/29 reflects a climatic amelioration of interstadial or interglacial status. Pollen assemblages from Saalian sediments in the uppermost part of the core indicate that the site of 81/29 received a strong influx of reworked material of British origin.

In **paper IV** a pollen stratigraphy from the 229 m deep BGS borehole 81/34 from the Devil's Hole area is presented (Fig. 1), in which twelve pollen assemblage zones are identified (1-12). The observation of massulae from *Azolla filiculoides* in sediment with reversed polarity at the base of 81/34 indicates an age younger than the Olduvai geomagnetic event for the entire sequence. The Early Pleistocene sediments were at least partly deposited in the vicinity of a river outlet and can be correlated either with the Eburonian or the Menapian cold stage and with the Bavel interglacial and the Linge glacial within the Bavelian stage in the Dutch stratigraphy. The Middle Pleistocene sequence contains an interval rich in *Abies*, *Picea* and *Pinus*, probably deposited during the end of either Cromerian Complex interglacial IV (Noordbergum) or possibly the Holsteinian. The uppermost 80 m of the core contains high frequencies of pre-Quaternary and deteriorated palynomorphs indicating extensive glacial or glaciofluvially reworked sediment.

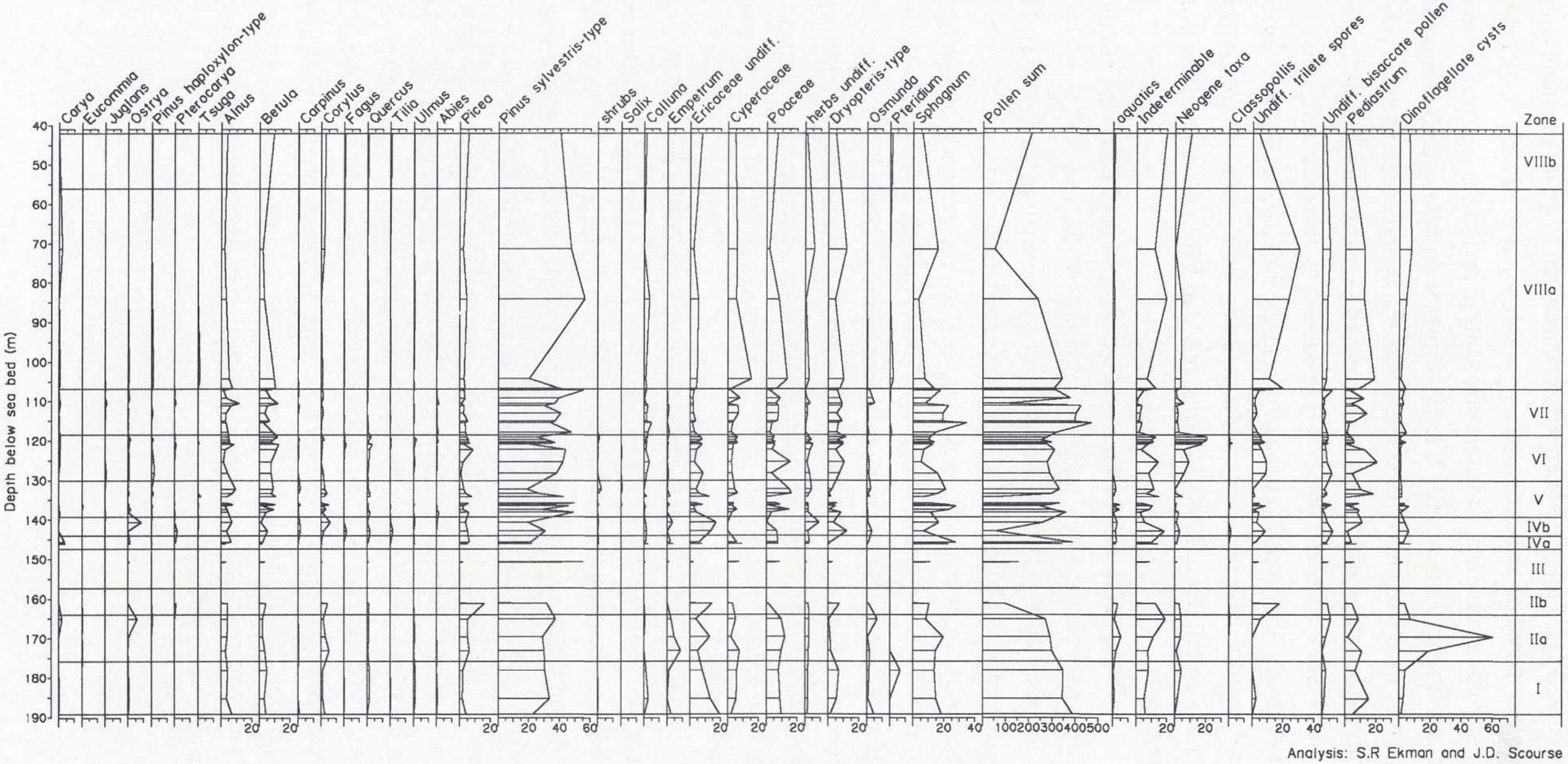

Fig. 6. Pollen percentage diagram, 81/26.

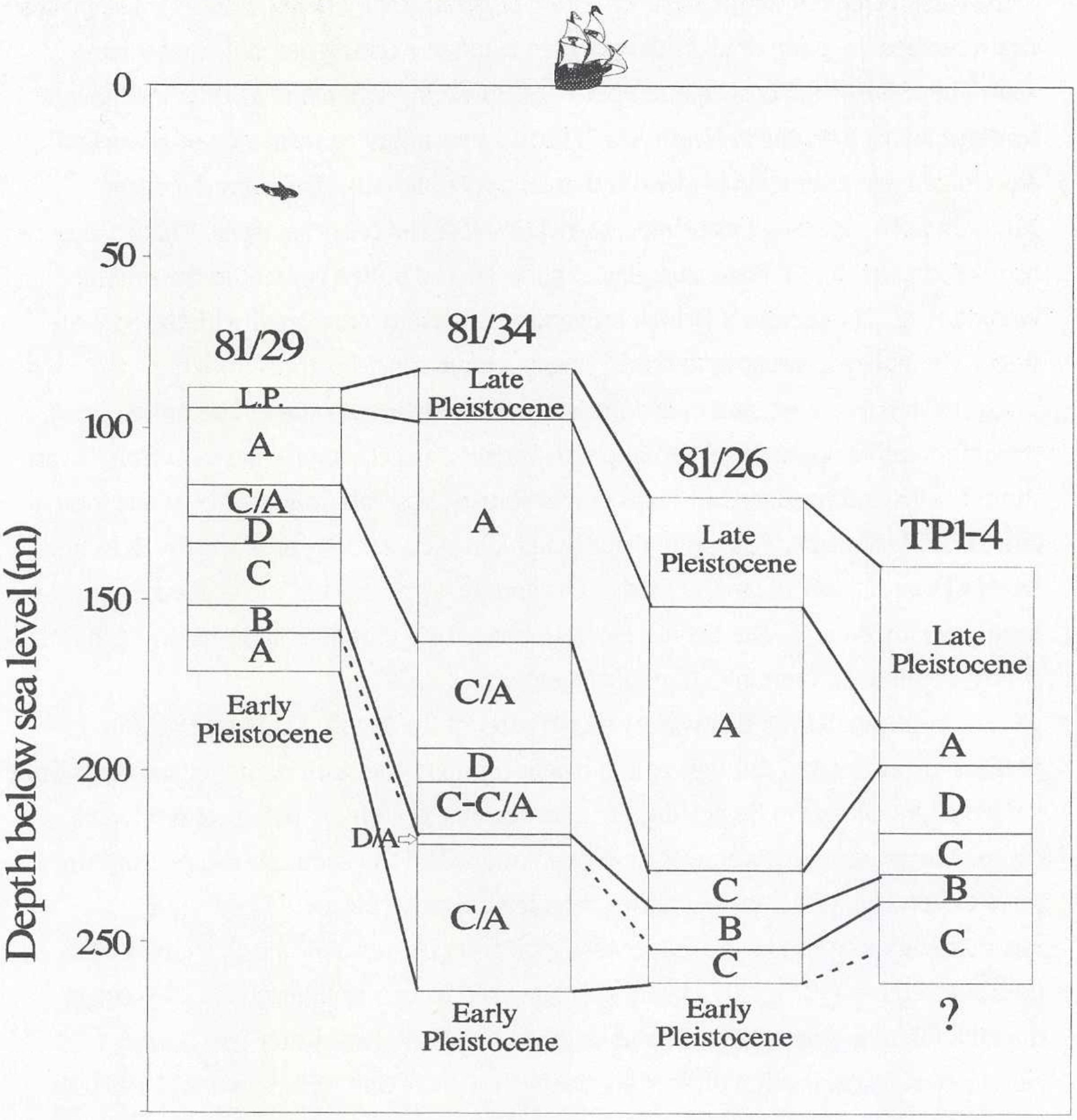

*Fig. 7. Pollen-based correlations of Middle Pleistocene sediments in the Devil's Hole sequences 81/29 and 81/34 and the Fladen Ground sequences 81/26 and TP1-4. **A** and **B** intervals are characterised by a pollen composition rich in pre-Neogene respectively Neogene palynomorphs and interpreted to indicate the influence of glacial debris eroded by the British respectively Scandinavian ice sheet. **C** intervals are characterised by high to relatively high values of non-arboreal pollen (NAP) and/or spores from mosses and ferns indicating an open landscape. **D** intervals are clearly dominated by pollen from boreal tree taxa indicating cool-temperate climatic conditions. The uppermost A intervals are possibly of Saalian age and the B intervals of Elsterian age.*

In **paper V** two Middle Pleistocene sequences from the Fladen Ground, 81/26 and TP1-4 (Jansen and Hensey, 1981), and two from the Devil's Hole area (81/29 and 81/34) are correlated on the basis of pollen biostratigraphy (Figs. 1 and 7). The pollen stratigraphies are compared, with reference taken to existing borehole and seismic data. The result (Fig. 7) is an attempt to generalise the schematic Middle Pleistocene stratigraphy of the central North Sea. The most pronounced influence of reworked pre-Quaternary sediments is identified in an upper interval, rich in pre-Neogene palynomorphs, and in a lower interval, rich in Neogene palynomorphs. This change can be related to Middle Pleistocene glacial periods. The pollen content in the younger interval (Fig. 7) indicates a British provenance, possibly correlated with the Saalian stage. The pollen content in the older interval indicates derivation from the Scandinavian ice sheet, and may correlate with the Elsterian stage. The pollen stratigraphies between these two intervals reflect a vegetational transition from dwarf shrub heaths and peatlands towards boreal forests, possibly followed by a return to a more open landscape. This pollen stratigraphical succession is best preserved in the Devil's Hole sequences. In the Fladen Ground the upper part of the sequence may have been glacially eroded. The Devil's Hole sequences are probably underlain by deltaic deposits of the Cromerian Complex and earlier.

In **paper VI** the Early Pleistocene parts of the 81/29, 81/34 and 81/26 pollen profiles are correlated through pollen biostratigraphy and with reference to pre-existing palaeomagnetic data. The profiles are also correlated with the pollen-based Dutch composite stratigraphy where a good correlation with the geomagnetic polarity time scale exists. Comparisions are drawn between existing palaeoenvironmental reconstructions from marine microfossil data from the profiles and from the Dutch pollen stratigraphy (Fig. 8). The Devil's Hole sequences are interpreted as younger than the Olduvai geomagnetic event as massulae of the freshwater fern *Azolla filiculoides*, a species that did not appear before that event (Gibbard *et al.*, 1991, cf. Bertelsen, 1972), is present in a reversed polarity sequence. Similar maximum age interpretation can be drawn for the Fladen Ground borehole. Considerable freshwater influx at the base of all three pollen profiles can probably be related to delta progradation from the south during Early Pleistocene times. In the Devil's Hole sequences, elevated frequencies of pre-Quaternary spores are also registered in the upper part of this freshwater-influenced interval, indicating onshore erosional activity, probably glaciation. This interval is interpreted as of Menapian age, a stage during which increased delta progradation in the North Sea and the first Quaternary regional glaciation occurred in NW Europe. An hiatus in the Devil's Hole vicinity separates the

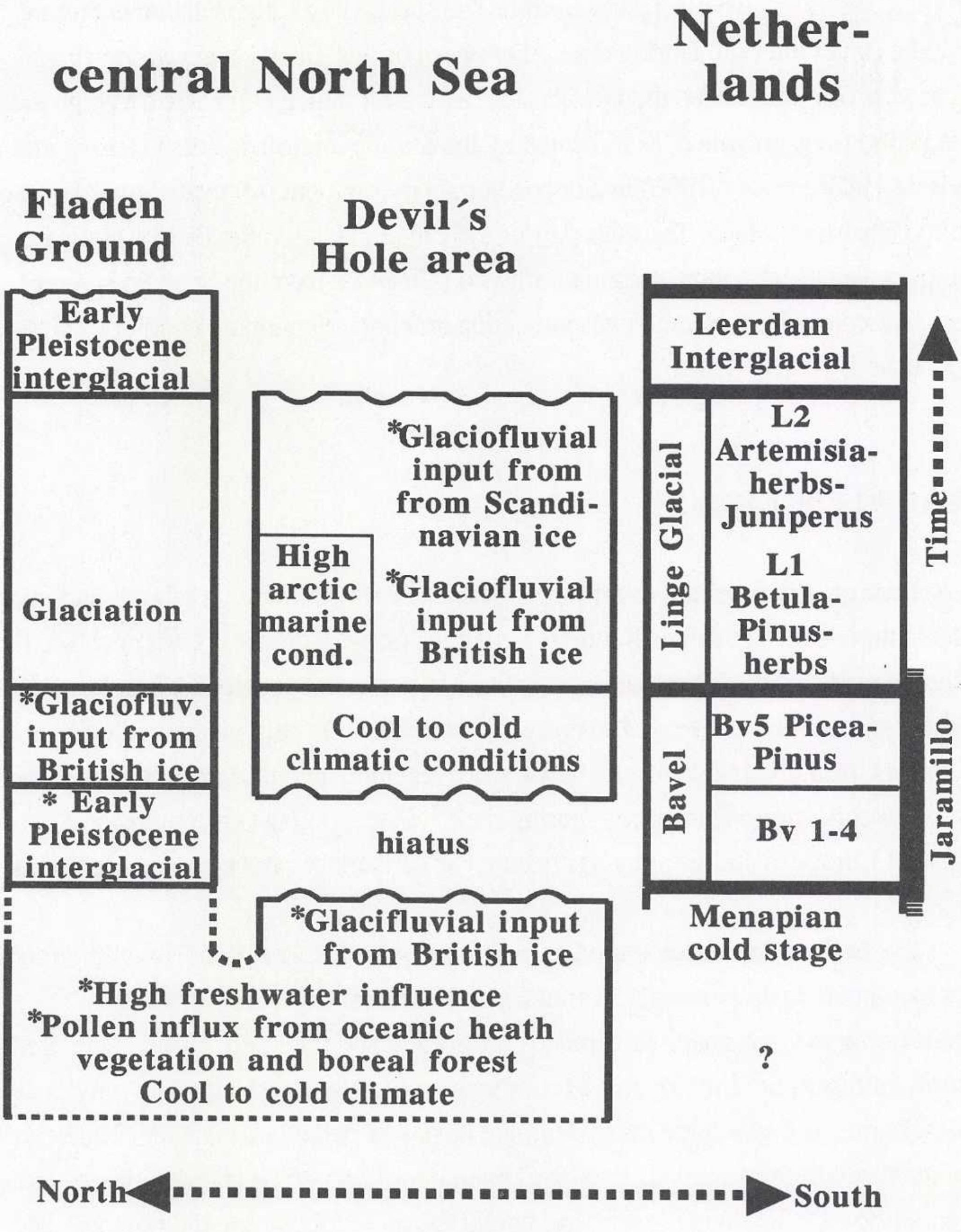

*Fig. 8. Suggested model for environmental changes in the central North Sea during the late part of the Early Pleistocene in NW Europe. * = interpretations based on the pollen content.*

Menapian interval from a sequence correlated with the latest part of the Bavel interglacial (Bv5) i.e., in the upper part of the Jaramillo geomagnetic event (cf. Zagwijn and De Jong, 1984). Marine microfossil assemblages in the latter interval indicate subarctic-arctic conditions (Harland, 1988; Jensen and Knudsen, 1988; Penney, 1990; Knudsen and Sejrup,1993) and in the Fladen Ground sequence a pollen flora indicates extensive glacial reworking. The succeeding Linge Glacial is present above the Bavel interval. During the earlier phase of this glacial stage strong fluvial discharge at first influenced the Devil's Hole area after which calm arctic to high arctic marine conditions prevailed, as indicated by the marine microfossil data (Jensen and Knudsen, 1988; Penney, 1990) in a depositional environment influenced by meltwater from the British ice sheet. The later part of the Linge glacial in the Devil's Hole area contains pollen spectra indicating glaciofluvial influences from the Scandinavian ice sheet and foraminiferal assemblages indicating ameliorated climatic conditions (Jensen and Knudsen, 1988).

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REFERENCES

Aguirre, E. and Pasini, G. 1985. The Plio-Pleistocene boundary. *Episodes*, *8*, 116-120.

Andrews, I.J., Long, D., Richards, P.C., Thomson, A.R., Brown, S., Chesher, J.A. and McCormac, M. 1990. *United Kingdom Offshore Regional Report: The Geology of the Moray Firth*. HMSO, London, 1-96.

Baumgartner, A. and Reichel, E. 1975. *The word water balance. Mean annual global, continental and maritime precipitation, evaporation and run-off*. Elsevier, Amsterdam. 1-179

Bertelsen, F. 1972. *Azolla* species from the Pleistocene of the central North Sea area. *Grana*, *12*. 131-145.

Bijslma, S. 1981. Fluvial sedimentation from the Fennoscandian area into the North-West European Basin during the Late Cenozoic. *Geologie en Mijnbouw 60*, 337-345.

Boulton, G.S. 1992. Quaternary. IN: P.McL.D. Duff and A.J. Smith (editors), Geology of England and Wales. London. *Geological Society*. 413-444.

Boulton, G.S. and Hindmarsh, R.C.A. 1987. Sediment deformation beneath glaciers: rheology and geological consequences. *Journal of Geophysical Research*, *92*. 9059-9082.

Bridgland, D.R. and D'Olier, B. 1995. The Pleistocene evolution of the Thames and Rhine drainage systems in the southern North Sea Basin. IN: R.C. Preece (editor), Island Britain: a Quaternary Perspective. *Geological Society Special Publication*, *96*. 27-46.

Cameron, T.D.J., Bonny, D.M., Gregory, D.M. and Harland, R. 1984. Lower Pleistocene dinoflagellate cysts, foraminiferal and pollen assemblages in the southern North Sea. *Geological Magazine, 121.* 85-79.

Cameron, T.D.J., Bulat, J. and Mesdag, C.S. 1993a. High resolution seismic profiles through a Late Cenozoic delta complex in the southern North Sea. *Marine and Petroleum Geology, 10.* 591-599.

Cameron, T.D.J., Crosby, A., Balson, P.S., Jeffery, D.H., Lott, G.K., Bulat, J. and Harrison, D.J. 1992. *United Kingdom Offshore Regional Report: The Geology of the Southern North Sea.* HMSO, London.

Cameron, T.D.J. Van Doorn, D., Laban, C. and Streif, H.J. 1993b. Geology of the Southern North Sea Basin. *Proc. 8th Symp. on Coastal and Ocean Management, American Shore and Beach Preservation Association/ASCE, New Orleans, Louisianna.* 14-26.

Cameron, T.D.J., Stoker, M.S. and Long, D. 1987. The history of Quaternary sedimentation in the UK sector of the North Sea basin. *Journal of Geological Society of London, 144.* 43-58.

Caston,V.N.D. 1977. A new isopachyte map of the Quaternary of the North Sea. In: Quaternary Deposits of the Central North Sea. *Rep. Inst. Geol. Sci. 77/11.* 1-8.

Cloething, S., Gradstein, F.M., Kooi, H., Grant, A.C. and Kaminski, M. 1990. Plate reorganisation: a cause of rapid late Neogene subsidence and sedimentation around the North Atlantic. *Journal of the Geological Society of London, 147.* 496-506.

Cross, A.T., Thompson, G.G. and Zaitzeff, J.B. 1966. Source and distribution of palynomorphs in bottom sediments, southern part of Gulf of California. *Marine Geology, 4.* 467-524.

Doppert, J.W.C., Ruegg, G.H.J., Van Staalduinen, C.J., Zagwijn, W.H. and Zandstra, J.G. 1975. Formaties van het Kwartair en Boven-Tertiair in Nederland. IN: W.H. Zagwijn and C.J. Van Staalduinen (editors), *Toelichtung bij geologische oversichtkaarten van Nederland.* Rijks Geologische Dienst, Haarlem. 11-56.

Ehlers, J., Meyer, K-.D. and Stephan H-.J. 1984. The pre-Weichselian glaciations of North-West Europe. *Quaternary Science Reviews, 3.* 1-40.

Ehlers, J. and Wingfield, R. 1991. The extension of the Late Weichselian/Late Devensian ice sheets in the North Sea Basin. *Journal of Quaternary Science, 6.* 313-326.

Eisma, D. and Kalf, J. 1979. Distribution and particle size of suspended matter in the Southern Bight of the North Sea and the Eastern channel. *Netherlands Journal of Sea Research, 13.* 298-324.

Eisma, D. and Kalf, J. 1987. Dispersal, concentration and deposition of suspended matter in the North Sea. *Journal of the Geological Society of London, 144*. 166-178.

Faegri, K. and Iversen, J. 1964. *Textbook of pollen analysis*. 2nd ed. Hafner Publishing Company, New York. 1-237.

Fairbanks, R.G. 1989. A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. *Nature, 342*. 637-642.

Funnell, B.M. 1995. Global sea-level and the (pen-)insularity of late Cenozoic Britain. IN: R.C. Preece (editor), Island Britain: a Quaternary Perspective. *Geological Society Special Publication, 96*. 3-13.

Funnell, B.M. 1996. Plio-Pleistocene Palaeogeography of the southern North Sea Basin (3.75-0.60 Ma). *Quaternary Science Reviews, 15*. 391-405.

Gatliff, R.W., Richards, P.C, Smith, K., Graham, C.C., McCormac, M., Smith, N.J.P., Long. D., Cameron, T.D.J., Evans, D., Stevenson, A.G., Bulat, J. and Ritchie, J.D. 1994. *United Kingdom Offshore Regional Report: The Geology of the central North Sea*. HMSO, London. 1-118.

Gibbard, P.L. 1988. The history of the great northwest European rivers during the past three million years. *Philosphcial Transactions of the Royal Society of London, 318B*: 559-602.

Gibbard, P.L. 1995. The formation of the Strait of Dover. IN: R.C. Preece (editor), Island Britain: a Quaternary Perspective. *Geological Society Special Publication, 96*. 15-27.

Gibbard, P.L., West, R.G., Zagwijn, W.H., Balson, P.S., Burger, A.W., Funnell, B.M., Jeffery, D.H., De Jong, J., Van Kolfschoten, T., Lister, A.M., Meijer, T., Norton, P.E.P., Preece, R.C., Rose, J., Stuart, A.J., Whiteman, C.A. and Zalasiewicz, J.A. 1991. Early and Early Middle Pleistocene Correlations in the Southern North Sea Basin. *Quaternary Science Reviews, 10*. 23-52.

Gijzel, P. Van, Overweel, C.J.and Veenstra, H.J. 1959. Geological investigation on boulder clay of E. Groningen. *Leidse Geologische Mededelingen, 24*. 721-759.

Glennie, K.W. 1990. Outline of North Sea history and structural framework. IN: K.W. Glennie (editor). *Introduction to the petroleum geology of the North Sea* (3rd edition). Oxford. Blackwell Scientific Publications. 34-77.

Groot, J. 1966. Some observations of pollen grains in suspension in the estuary of the Delaware River. *Marine Geology, 4*. 409-416.

De Haas, H. 1996. Recent sediment accumulation and organic carbon burial in the North Sea sediment. IN: Sundqvist B. (editor), Short Papers and Abstracts for the Jubilee Meeting "Current Problems, Ideas and Results in Geology". *Geologiska Föreningens i Stockholm Förhandlingar, 118.* A81.

De Haas, H., Okkels, H. and van Weering, T.C.E. 1996. Recent sediment accumulation in the Norwegian Channel, North Sea. *NGU Bull., 430*, 57-65.

Harland, R. 1988. Quaternary dinoflagellate cyst biostratigraphy of the North Sea. *Palaeontology, 31.* 877-903.

Harland, R., 1995. Investigation into the Dinoflagellate Cyst Content of Two Quaternary Samples from British Geological Survey Boreholes, 81/26 and 81/34, central North Sea. DinoData Services. Report RH/95/04/02.

Head, M.J. 1994. Morphology and palaeoenvironmental significance of the Cenozoic dinoflagellate genera *Tectatodinium* and *Habibacysta. Micropalaeontology, 40.* 289-321.

Heusser, L.E. 1978. Spores and Pollen in the marine realm. IN: B.U. Haq and A. Boersma (editors), *Introduction to marine micropaleontology.* Elsevier. Amsterdam. 327-339.

Heusser, L.E. 1988. Pollen distribution in marine sediments on the continental margin off northern California. *Marine Geology, 80.* 131-147.

Heusser, L.E. and Balsam, W.B. 1977. Pollen distribution in the northeast Pacific Ocean. *Quaternary Research, 7.* 45-62.

Hilgen, F.J. 1991. Astronomical calibration of Gauss to Matuyama sapropels in the Mediterranean and implication for the Geomagnetic Polarity Time Scale. *Earth and Planetary Science Letters*, 104. 226-244.

Holmes, R., 1977. Quaternary deposits of the central North Sea, 5. The Quaternary geology of the UK sector of the North Sea between 56° and 58° N. *Inst Sci. Rep. 77.14.*

Hooghiemstra, H. 1988. Palynological records from northwest African marine sediments: a general outline of the interpretation of the pollen signal. *Philosphcial Transactions of the Royal Society of London, B318.* 431-449.

Jansen, J.H.F. 1976. Late Pleistocene and Holocene history of the northern North Sea, based on acoustic reflection records. *Netherlands Journal of Sea Research, 10.* 1-43.

Jansen, J.H.F., Doppert, J.W.C., Hoogendoorn-Toering, K., De Jong, J. and Spaink, G., 1979b. Late Pleistocene and Holocene deposits in the Witch and Fladen Ground area, northern North Sea. *Netherlands Journal of Sea Research, 13*, 1-39.

Jansen, J.H.F. and Hensey, A.M. 1981. Interglacial and Holocene sedimentation in the North Sea, an example of Eemian deposits in the Tartan Field. *Special Publication of the International Association of Sedimentologists, 5.* 323-334.

Jansen, J.H.F., Van Weering, Tj.C.E. and Eisma, D. (1979b). Late Quatermary sedimentation in the North Sea. IN: E. Oele, R.T.E. Schüttenhelm and A.J. Wiggers (editors), The Quaternary History of the North Sea. *Acta Univ. Ups. Symp. Univ. Ups. Annuum Quingentesimum Celebrantis, 2,* 115-142.

Jelgersma, S. 1979. Sea-level changes in the North Sea basin. In: E. Oele, R.T.E. Schüttenhelm and A.J. Wiggers (editors), The Quaternary History of the North Sea, *Acta Universitatis Upsaliensis Symp. Univ. Ups. Ann. Quingent. Cel. 2.* 233-248.

Jensen K.A. and Knudsen K.L. 1988. Quaternary foraminiferal stratigraphy in boring 81/29 from the central North Sea. *Boreas, 17.* 273-287.

De Jong, J. 1981. Pollen-analytical investigation of ice-pushed deposits of the Utrechtse Heuvelrug at Rhenen, The Netherlands. *Mededelingen Rijks Geologische Dienst, 35.* 192-203.

De Jong, J. 1988. Climatic variability during the past three million years, as indiciated by vegetational evolution in northwest Europe with emphasis on data from the Netherlands. *Philosophical Transactions of the Royal Society of London B 318.* 603-617.

Knudsen, K.L. and Sejrup H.P. 1993. Pleistocene stratigraphy in the Devil's Hole area, central North Sea: foraminiferal and amino-acid evidence. *Journal of Quaternary Science, 8,* 1-14.

Kooi, H., Hettema, M. and Cloething, S., 1991. Lithospheric dynamics and the rapid Pliocene subsidence phase in the southern North Sea basin. *Tectonophysics, 192.* 245-259.

Lambeck, K. 1993. Glacial rebound on the British Isles - I. A high resolution, high-precision model. *Geophysical Journal International, 115.* 960-990.

Linke, G., Katzenberger, O. and Grün, R. 1985. Description and ESR dating of the Holstein Interglaciations. *Quaternary Science Reviews,* **4**, 319-331.

Long, D., Laban, C., Streif, H., Cameron, T.D.J. and Schüttenhelm, R.T.E., 1988. The sedimentary record of climatic variation in the southern North Sea. *Philosophical Transactions of the Royal Society of London, B318,* 523-537.

Longva, O., Sæther, O.M., Klungsøyr, J., Faye, G. and Thorsnes, T. 1996. Contaminant-supply to the Skagerrak sediments - a retrospect of the last centuries. IN: Sundqvist B. (editor), Short Papers and Abstracts for the Jubilee Meeting "Current Problems, Ideas and Results in Geology". *Geologiska Föreningen i Stockholm Förhandlingar, 118.* 82.

Lüttig, G. and Marleveld, G.C. 1961. Nordische Gesciebe in Ablagerungen prä Holstein in den Niederlanden (Komplex von Hattem). *Geologie en Mijnbouw, 40* . 163-174.

Mangerud, J., Andersen, S.T., Berglund, B.E. and Donner, J.J. 1974. Quaternary stratigraphy of Norden, a proposal for terminology and classification. *Boreas, 3*. 109-126.

McCave, I.N., 1973. Mud in the North Sea. IN: E.D. Goldberg (editor), *North Sea Science*. Cambridge, Mass: MIT. 75-100.

McCave, I.N., Caston, V.N.D. and Fannin, N.G.T., 1977. The Quaternary of the North Sea. IN: F.W. Shotton, (editor), *British Quaternary Studies, Recent Studies*, Clarendon, Oxford. 187-204.

Meijer, T. and Preece, R.C. 1995. Malacological evidence relating to the insularity of the British Isles during the Quaternary. IN: R.C. Preece (editor), Island Britain: a Quaternary Perspective. *Geological Society Special Publication, 96*. 89-110.

Melia, M.B. 1984. The distribution and relationship between palynomorphs in aerosols and deep-sea sediments off the coast of northwest Africa. *Marine Geology, 58*. 345-371.

Menke, B. 1968. Beiträge zur Biostratigraphie des Mittelpleistozäns in Norddeeutschland. *Meyniana, 18*. 35-42.

Moodley, L. and van Weering, T.C.E. 1993. Foraminiferal record of the Holocene development of the marine environment in the southern North Sea. *Netherlands Journal of Sea Research, 31*. 43-52

Mudie, P.J. 1982. Pollen distribution in recent marine sediments, eastern Canada. *Canadian Journal of Earth Sciences, 19*. 729-747.

Mudie, P.J. and Matthiessen, J. 1988. Dinoflagellates, pollen/spore assemblages and related studies. IN: J. Thiede (editor), Scientific Cruise report of Arctic Expedition *ARK IV/3. Ber. Polarforsch., 43*. 92-97.

Mudie, P.J. and McCarthy, F.M.G. 1994. Late Quaternary pollen transport processes, western North Atlantic: Data from box models, cross margin and N-S transects. *Marine Geology, 118*. 79-105.

Muller, J., 1959. Palynology of recent Orinoco delta and shelf sediments. *Micropalaeontology*, 5. 1-32.

Murray, J.W. 1992. Distribution and population dynamics of benthic foraminifera from the southern North Sea. *Journal of Foraminiferal Research, 22*. 114-128.

Otto, L. 1976. Problems in the application of reservoir theory to the North Sea. *ICES, Hydrological Comm. CM 1976/C, 18*. 1-17.

Otto, L., Zimmerman, J.T.F., Furnes, G.K., Mork, M., Saetre, R. and Becker, G. 1990. Review of the physical oceanography of the North Sea. *Netherlands Journal of Sea Research, 26.* 161-238.

Pantin, H.M. 1991. The sea-bed sediments around the United Kingdom. Their bathymetric and physical environment, grain size, mineral composition and associated bedforms. *British Geological Survey. Keyworth, Nottingham.* 1-47.

Penney, D.N. 1990. Quaternary ostracod chronology of the central North Sea: the record from BH 81/29. *Courier Forschunginstitut Senckenberg, 123,* 97-109.

Polak, B. 1963. The sub-soil of the Bleeke Meer, compared to the fluvio-glacial deposits of Speulde. *Mededelingen Geologische Stichtung, 16.* 39-47.

Rousseau, D-D., Puisségur, J-J. and Lecolle, F. 1992. West-European terrestrial mollusc assemblages of isotopic stage 11 (Middle Pleistocene): climatic implications. *Palaeogeography, Palaeoclimatology, Palaeoecology, 92,* 15-29.

Ruegg, G.H.J. and Zandstra, J.G. 1977. Pliozäne und pleistozäne gestauchte Ablagerungen bei Emmerschans (Drenthe, Niederlande). *Mededelingen Rijks Geologische Dienst, 28.* 65-99.

Sclater, J.G. and Christie, P.A.F. 1980. Continental stretching: an explanation of the post-mid-Cretaceous subsidence of the central North Sea basin. *Journal of Geophysical Research, 85,* 3711-3739.

Scourse, J.D. and Austin, R.M. 1995. Palaeotidal modelling of continental shelves: marine implications of a land bridge in the Strait of Dover during the Holocene and Middle Pleistocene. IN: R.C. Preece (editor), Island Britain: a Quaternary Perspective. *Geological Society Special Publication, 96.* 75-88.

Sejrup, H.P., Aarseth, I., Ellingsen, K.L., Reither, E., Jansen, E., Løvlie, R., Bent, A., Brigham-Grette, J, Larsen, E. and Stoker, M. 1987. Quaternary stratigraphy of the Fladen area, central North Sea: a multidisciplinary study. *Journal of Quaternary Science, 2.* 35-58.

Sejrup, H.P., Aarseth, I., Haflidason, H., Løvlie, R., Bratten, Å., Tjøstheim, G., Forsberg, C.F. and Ellingsen, K.L. 1995. Quaternary of the Norwegian Channel: glaciation history and palaeoceanography. *Norsk Geologisk Tidskrift, 75.* 65-87.

Sejrup, H.P., Haflidason, H., Aarseth, I., King, E., Forsberg, C.F., Long, D. and Rokoengen, K. 1994. Late Weichselian glaciation history of the northern North Sea. *Boreas, 23.* 1-13

Sejrup, H.P. and Knudsen, K.L., 1993. Paleoenvironments and correlations of interglacial sediments in the North Sea. *Boreas, 22.* 223-235.

Shackleton, N.J., Berger, A. and Peltier, W.R. 1991. An alternative astronomical calibration of the lower Pleistocene timescale based on ODP Site 677. *Transactions of the Royal Society of Edinburgh, 81.* 252-261.

Shotton, F.W. 1973. General principles governing the subdivision of the Quaternary System. IN: G.F. Mitchell, L.F., Penny, F.W., Shotton, R.G. and West, (editors). A correlation of Quaternary deposits in the British Isles. *Geological Society of London, Special Report 4*. 1-7.

Smith, A.J., 1992. Offshore Geology. IN: P.McL.D. Duff and A.J. Smith (editors), Geology of England and Wales. London. *Geological Society*. 445-488.

Stoker, M.S. and Bent, A. 1985. Middle Pleistocene glacial and glaciomarine sedimentation in the west central North Sea. *Boreas, 14*. 325-332.

Stoker, M.S. and Bent, A. 1987. Lower Pleistocene deltaic and marine sediments in boreholes from the central North Sea. *Journal of Quaternary Science, 2*. 87-96.

Stoker, M.S., Long, D. and Fyfe, J.A. 1985. A revised Quaternary stratigraphy for the central North Sea. *British Geological Survey, Report, 17*. 1-35.

Stoker, M.S., Skinner, A.C., Fyfe, J.A. and Long, D. 1983. Palaeomagnetic evidence for early Pleistocene sediments in the central and northern North Sea. *Nature*, 304, 332-334.

Svendsen, E., Sætre, R. and Mork, M., 1991. Features of the northern North Sea circulation. *Continental Shelf Research, 11*. 493-508.

Sverdrup, H.U., Johnson, MW. and Fleming, R.H., 1942. *The Oceans, their physics, chemistry, and general biology*. New York, Prentice-Hall, Inc. 1-1087.

Valet, J.-P. and Meynadier, L. 1993. Geomagnetic field intensity and reversals during the past four million years. *Nature, 366*. 234-238.

Van der Hammen, T.H., Wijmstra, T.M. and Zagwijn, W.H. 1971. The floral record of the late Cenozoic of Europe. IN: K.K: Turekian (editor), *The late Cenozoic glacial ages*. Yale University Press, New Haven. 391-424.

Van Voorthuysen, J.H., Toering, K. and Zagwijn, W.H. 1972. The Plio-Pleistocene boundary in the North Sea basin. Revision of its position in the marine beds. *Geologie en Mijnbouw*, 51, 627-639.

Veenstra, H.J. 1970. Sediments of the southern North Sea. ICSU-SCOR Working Party Symposium, Cambridge, 3. 13-23

Veldkamp, A. and van den Berg, M.W. 1993. Three-dimensional modelling of Quaternary fluvial dynamics in a climo-tectonic dependent system. A case study of the Maas record (Maastricht, The Netherlands). *Global and Planetary Change, 8*. 203-218.

Van Weering, T.C.E. 1981. Recent sediments and sediment transport in the northern North Sea; surface sediments of the Skagerrak. *Spec. Publ. Int. Ass. Sediment. 5*, 335-359.

West, R.G. 1961. Vegetational history of the Early Pleistocene of the Royal Society Borehole at Ludham, Norfolk. *Proceedings of the Royal Society of London, B155.* 437-453.

West, R.G. 1980. Pleistocene forest history in East Anglia. *New Phytologist, 85*, 571-622.

West, R.G., Funnell, B.M., and Norton, P.E.P. 1980. An Early Pleistocene cold marine episode in the North Sea: pollen and faunal assemblages at Covehite, Suffolk, England. *Boreas, 9.* 1-10.

West, R.G., Knudsen, K.L., Penney, D.N., Preece, R.C. and Robinson, J.E. 1994. Palaeontology and taphonomy of Late Quaternary fossil assemblages at Somersham, Cambridgeshire, England, and the problems of reworking. *Journal of Quaternary Science, 9.* 357-366.

Wingfield, R.T.R. The origin of Major incisions within the Pleistocene Deposits of the North Sea. *Marine Geology, 91.* 31-52.

Zagwijn, W.H. 1960. Aspects of the Pliocene and Early Pleistocene Vegetation in the Netherlands. *Mededelingen Geologische Stichtung, C111-1, 5.* 1-85.

Zagwijn, W.H. 1973. Pollenanalytical studies of Holsteinian and Saalian Beds in The Northern Netherlands. *Medelingen Rijks Geologische Dienst, 24.* 139-156.

Zagwijn, W.H. 1979. Early and Middle Pleistocene coastlines in the southern North Sea Basin: In: E. Oele, R.T.E. Schüttenhelm and A.J. Wiggers (editors), The Quaternary History of the North Sea, *Acta Universitatis Upsaliensis Symp. Univ. Ups. Ann. Quingent. Cel. 2.* 31-42.

Zagwijn, W.H. 1985. An outline of the Quaternary stratigraphy of the Netherlands. *Geologie en Mijnbouw, 64.* 17-24.

Zagwijn, W.H., 1989. The Netherlands during the Tertiary and the Quaternary: A case history of Coastal Lowland evolution. *Geologie en Mijnbouw, 68.* 107-120.

Zagwijn, W.H. and De Jong, J. 1984. Die interglaziale von Bavel und Leerdam und ihre stratigraphische Stellung in Niederländischen Früh-Pleistozän. *Mededelingen Rijks Geologische Dienst, 37*, 155-169.

Zagwijn, W.H., and Veenstra, H.J. 1966. A pollen-analytical study of cores from the Outer Silver Pit, North Sea. *Marine Geology, 4.* 535-551.

Zalasiewicz, J.A., Mathers, S.J., Gibbard, P.L., Peglar, S.M., Funnell, B.M., Catt, J.A., Harland, R., Long, P. and Austin, T.J.F. 1991. Age and relationships of the Chilleford Clay (early Pleistocene: Suffolk, England). *Philosophical Transactions of the Royal Society of London, 333.* 81-100.

Zandstra, J.G. 1971. Geologisch onderzoek in de stuwwal van de oostelijke Veluwe bij Hattem en Wapenveld. *Mededelingen Rijks Geologische Dienst*, 22. 215-258.

Zandstra, J.G. 1983. Fine gravel, heavy mineral and grain-size analyses of Pleistocene, mainly glaciogenic deposits in the Netherlands. IN: J. Ehlers (editor), *Glacial deposits in north-west Europe*. Balkema. Rotterdam. 361-377.

Ziegler, P. A. and Louwerens, C.J. 1979. Tectonics of the North Sea. In: E. Oele, R.T.E. Schüttenhelm and A.J. Wiggers (editors), The Quaternary History of the North Sea, *Acta Universitatis Upsaliensis Symp. Univ. Ups. Ann. Quingent. Cel. 2*. 7-22.

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