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The Sedimentary Record of Climatic Variation in the Southern North Sea [and Discussion]

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The sedimentary record of climatic variation in the southern North Sea

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The sedimentary sequence on the shelf of the southern North Sea records Quaternary climatic changes in two ways. They are indicated directly by moraine and glaciofluvial deposits from the Elsterian, Saalian and Weichselian glacial periods when the British and the Scandinavian ice sheets covered parts of the area. An indirect response to the climate is indicated by sea-level changes. Phases of cooling are characterized by regressions and low sea-level stands; phases of warming are indicated by marine transgressions and high sea levels during the Holsteinian, Eemian and Holocene periods. The seismic characteristics of the different lithological units, the sedimentary sequences and their fossil content are described for the offshore area and the adjacent coastal zone. This provides a record of the interaction of sedimentary processes and the palaeogeographic development as a response to climatic changes.

1. Introduction

In the study of Quaternary deposits, the marine environment has a major advantage over terrestrial localities, where the Quaternary record is often fragmentary and is strongly influenced by local geographical factors. Although the deep ocean record is usually complete, it is normally very condensed and gives little opportunity to identify small-scale fluctuations in the environmental history of an area. Such sites also tend to lie a great distance from the major regional factor in sedimentation and control on climatic history, namely the continental glaciations. The Quaternary deposits on the continental shelves are much thicker, provide a more continuous record than those found on land, and are influenced to a much greater extent by nearby glaciations than deep-ocean sediments. In the North Sea they also provide essential evidence for the cross-correlation of the Quaternary stratigraphies already identified on land, between the U.K. and continental northwestern Europe.

The present state of knowledge on the geology of the southern North Sea is highly variable. In the British and Dutch sectors, systematic geological surveys are in progress, and the initial results have been published in several papers and in a set of geological maps at a scale of 1:250000, depicting the solid geology, the Quaternary geology and the sea bed sediments. In the Belgian, German, and Danish sectors there is a less dense grid of observations and systematic investigation of the Quaternary deposits is at an early stage. Nevertheless, the present information can be used to interpret the sedimentary sequences in the southern North Sea with regard to their evidence for Quaternary climatic changes. These changes are indicated in two ways. During the Elsterian (Anglian), Saalian (Wolstonian) and Weichselian (Devensian) glacial periods, the British and the Scandinavian ice sheets covered parts of the

North Sea area and deposited moraine, glaciofluvial, and glaciolacustrine deposits. An indirect response to the climate is indicated by sea-level changes. Phases of cooling are characterized by regressions and low sea-level stands; phases of warming are indicated by marine transgressions and high sea levels during the Holsteinian (Hoxnian) and Eemian (Ipswichian) interglacial periods and the Holocene. Similar marine regressions and transgressions have been interpreted from the early Pleistocene deposits. By the interaction of these processes, complicated patterns and sequences of sedimentary units were formed. The stratigraphy and the suggested correlation of the sedimentary units in the southern North Sea is illustrated in figure 1; the stratigraphic range of the Quaternary facies units in the southern, central and northern North Sea is shown in figure 2.

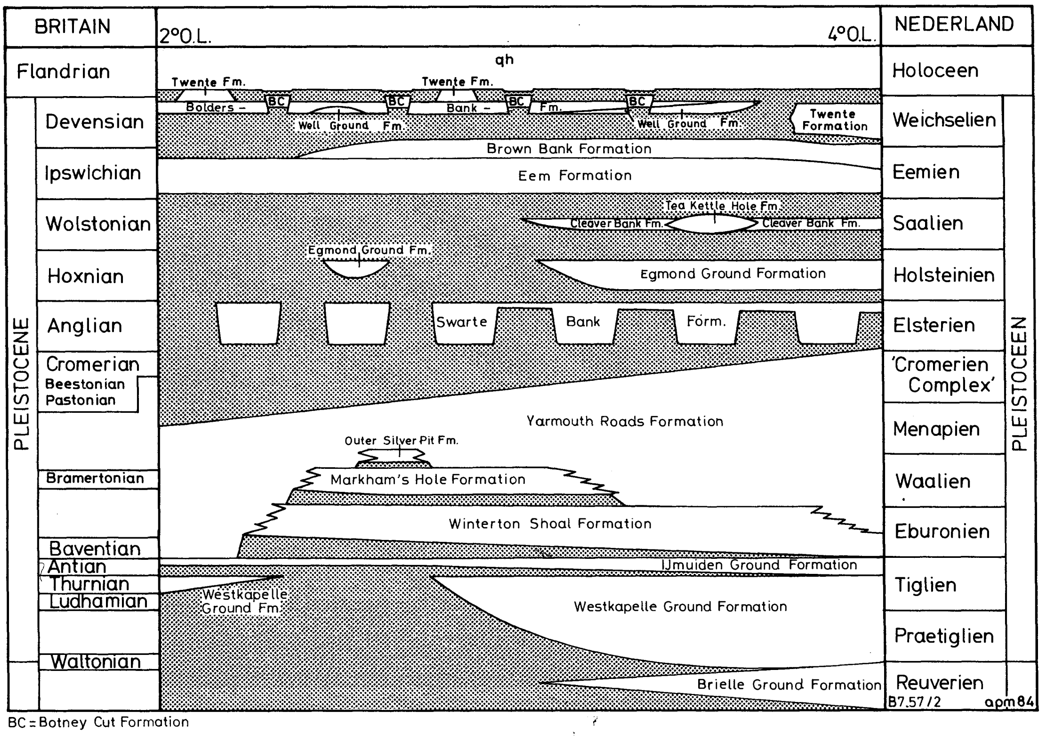

FIGURE 1. Suggested correlation of the Pleistocene formations in the southern North Sea with the Quaternary Stages of Britain and The Netherlands.

The climatic history of the North Sea has been deduced from the interpretation of seismic profiles of the offshore Quaternary deposits and the analyses of many boreholes and sea bed samples. The borehole samples have been subjected to micropalaeontological analyses, relative and absolute age determinations (amino-acid and carbon-14), and microfabric examination. Their geotechnical properties have been tested where possible and argillaceous horizons, where appropriate, have been tested for their primary palaeomagnetic polarity. These analyses were aimed at correlating the seismostratigraphy with borehole evidence from the offshore and onshore areas and at determining the age and depositional environments of the sediments, their subsequent geological history, and to identify periods of non-deposition and possible erosion.

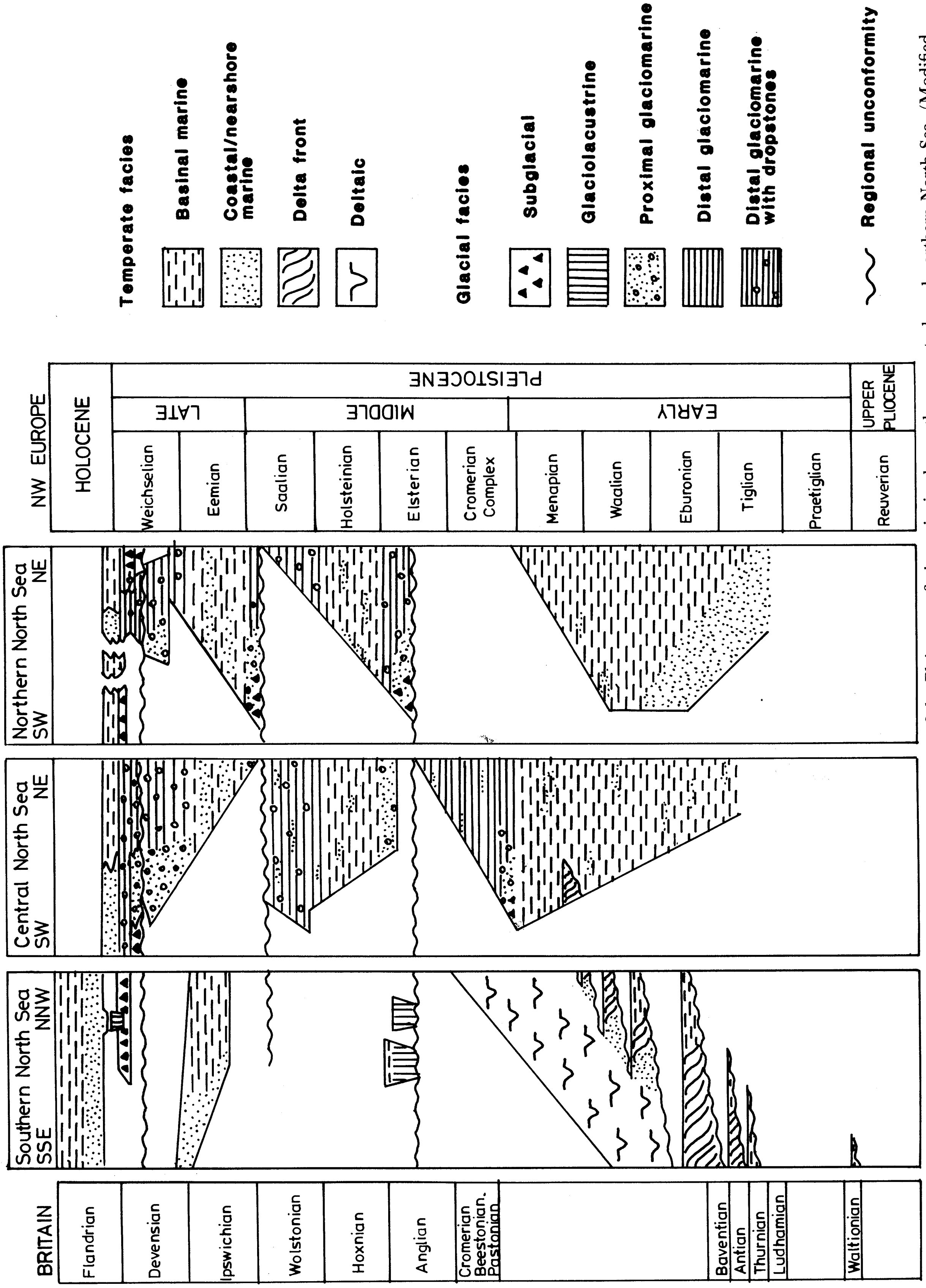

Figure 2. Schematic diagram summarizing the stratigraphic range of the Pleistocene facies units in the southern, central, and northern North Sea. (Modified from Cameron *et al.* 1987.)

2. The Quaternary stratigraphy

2.1. *The base of the Quaternary*

The lower boundary of the Pleistocene sequence in the British sector of the North Sea is now taken at the top of the Red Crag, an Upper Pliocene formation consisting of shell-bearing glauconitic sediment, which occurs at or near the sea bed off the coast of East Anglia (Balson & Cameron 1985). In the Dutch sector, Pliocene sandy and clayey marine sediments have been classified in the Brielle Ground Formation (Cameron *et al.* 1988), and the boundary is taken at the first significant climatic deterioration in the pollen record or somewhat below the FA_1–FA_2 foraminiferan zone boundary (Doppert 1975). In Germany the Pliocene–Pleistocene boundary is taken at the top of the *Kaolinsand*, Sylt-Stufe; the *Kaolinsand* is a coarse-grained whitish quartz sand with bleached and decomposed feldspars and local seams of lignite, which can be placed palynologically into the Pliocene, Reuverian stage. Lithologically the boundary is placed at the base of sands with so called 'nordic components', which have been derived from Scandinavian rocks.

The Pliocene–Pleistocene boundary in the North Sea lies close to the transition between the Matuyama and Gauss polarity epochs, dated at about 2.47 Ma BP. In the southernmost North Sea this boundary occurs at or near an unconformity coincident with a major change in the type of sedimentation offshore, and the sediments overlying the unconformity have mainly reversed magnetic polarity (Cameron *et al.* 1984). The base of the Quaternary in the central and northern North Sea is less easily identified and the Quaternary often appears conformable on Pliocene sediments in the centre of the North Sea. In these areas, the base of the Quaternary has been deduced from micropalaeontological or palaeomagnetic evidence. Close to the Scottish coast, Pleistocene sediments lie unconformably upon easterly dipping Devonian to Tertiary sediments.

2.2. *The Lower to early Middle Pleistocene*

In the North Sea, the Lower to early Middle Pleistocene sediments are mainly marine. In the southern North Sea the early Pleistocene succession displays many of the seismic characteristics of delta-related sediments (Westkapelle Ground Formation, IJmuiden Ground Formation, Smith's Knoll Formation, Winterton Shoal Formation and Yarmouth Roads Formation (figure 1)) and all the seismic facies can be related to a specific environment within, or offshore from, a delta complex (Cameron *et al.* 1987). This agrees with stratigraphical evidence in the Netherlands for a massive expansion of north European rivers into the North Sea Basin during early Pleistocene times (Zagwijn 1974). On the basis of micropalaeontological data, a series of palaeogeographical maps were constructed by Zagwijn (1979) to illustrate the offshore expansion of the delta complex from the Tiglian (2.1–1.7 Ma BP) through the Waalian (1.3–0.95 Ma BP) to the Cromerian (*ca.* 0.7–0.4 Ma BP) stage. His maps suggest that the delta complex had expanded across the German sector of the North Sea by Cromerian times.

Examination of marine flora (dinoflagellate cysts) and fauna (foraminifera) from boreholes in the southern North Sea suggests deposition in a climate as warm as, and possibly warmer than, that at present (Cameron *et al.* 1984). However, redeposited terrestrial pollen assemblages indicate a wider range of climatic conditions with fluctuations between boreal and mixed coniferous–deciduous regional forest cover; these results suggest alternation between relatively cool and warm temperate climatic conditions. This may be due to the mixing of pollen derived by river transport and wind from several different source areas, and the pollen assemblages may have been further complicated by resedimentation offshore. The Lower Pleistocene succession appears to represent a series of marine transgressions and regressions, perhaps recording the effects of eustatic sea-level changes on sedimentation on the periphery of the North Sea Basin, with periods of marine regression corresponding to periods of maximum climatic deterioration. However, differential isostatic movements between the North Sea Basin and peripheral areas may also have caused geographic and quantitative changes in sediment supply by various west-flowing rivers. Periods of maximum climatic deterioration may be expected to correspond with regional lowering of sea level and a transfer of marine sedimentation to the outer margins of the continental shelf. This may account for the absence of cool-temperature influences on the marine fossil assemblages in the southern North Sea.

The central North Sea deposits also contain evidence for deltaic sedimentation in the early Pleistocene (Stoker & Bent 1988), but include a greater proportion of prodelta and fully marine sediments and are believed to represent a more complete stratigraphic sequence than that preserved in the southern North Sea. Stoker & Bent (1988) suggest that major deltas of the North European Plain eventually coalesced with the much smaller local deltas of eastern Britain, most notably of an ancestral Tay–Forth estuarine system. The fossil assemblages contain evidence for a more varied climate here than in the southern North Sea, although, in general, warm temperate climatic conditions prevailed during deposition of the sedimentary sequence (Stoker *et al.* 1985); warm temperate deposits of Tiglian age have also been recorded from the Danish sector (Bertelsen 1972).

2.3. *The late Middle and Upper Pleistocene*

The Lower and early Middle Pleistocene deposits of the North Sea Basin are truncated by a regional unconformity of Elsterian age. Above the Middle Pleistocene Brunhes–Matuyama magnetic reversal, there is sedimentological and marine floral and faunal evidence in the central and northern North Sea for a dramatic deterioration in climatic conditions before the major seismic unconformity evident throughout the U.K. sector (the tops of the Yarmouth Roads, Aberdeen Ground and Shackleton Formations).

Sedimentation in the North Sea Basin has been dominated by glacial erosional and depositional processes since mid-Quaternary times. The base of the Upper Pleistocene succession in the Southern Bight is a gently undulating erosional unconformity less than 40 m below sea bed (less than 80 m below present sea level). Three regional glaciations affected northwest Europe to a variable extent during the Elsterian (Anglian), Saalian (Wolstonian) and Weichselian (Devensian) glacial stages, when ice sheets covered much of Britain, Scandinavia, Denmark, northern Germany and the Netherlands. Likewise, three major glacial episodes have been identified within the Middle and Upper Pleistocene sediments of the North Sea. The landforms and deposits associated with each episode are broadly similar but are separated by interglacial marine sediments.

2.3.1. *Elsterian glacial period*

In the southern North Sea, the earliest glacial conditions are represented by local ice-push deformation of the Lower to early Middle Pleistocene deposits in the Brown Bank area, and at the eastern margin of the Flemish Bight sheet in the Netherlands sector of the North Sea (Laban *et al.* 1984; Cameron *et al.* 1988). These features demonstrate that the margin of the Elsterian ice sheet extended southwards to at least 52° 20′ N. The Anglian tills cover much of

East Anglia and extend as far south as Ipswich (52° N). However, the Elsterian (Anglian) tills of East Anglia do not extend east of the present British coastline or have been eroded since Elsterian times.

In north Germany and in the Netherlands, a complex system of anastomosing subglacial valleys was eroded and infilled during the Elsterian glaciation (Kuster & Meyer 1979; Ehlers *et al.* 1984); similar valleys are eroded into early Middle and Lower Pleistocene and Tertiary sediments in the British and Dutch sectors of the North Sea, mainly to the north of 53° N. These valleys are typically aligned north–south or, in the UK sector, NNW–SSE. They are a few kilometres wide, and the largest has a maximum depth of 450 m (510 m below sea level) at 53° 16′ N and 3° E. All the valleys have a conspicuously undulating *thalweg*. The infill of these valleys, the Swarte Bank Formation, comprises a complex sequence of sediments. The basal unit, which is structureless or has a chaotic reflector configuration, has zones of reduced acoustic penetration and may consist of gravelly coarse sand, slump beds or perhaps, locally, till deposited penecontemporaneously with valley incision. The second well-bedded unit contains rare subparallel, high-amplitude reflectors at similar intervals and depth in adjacent valleys; this observation suggests that some of the valleys formed an interconnecting network of depressions during the stage of filling. This layered unit consists of glaciolacustrine clay with beds of silty clay and fine grained sand. The third unit of infill is mostly less than 30 m thick and is characterized by gently inclined, low- or moderate-amplitude reflections on the seismic profiles. This unit may represent a delta-related influx of fine-grained sands and clays into a glaciolacustrine environment comparable to the *potklei* in the Netherlands and the Lauenburg Clay of northwestern Germany.

It is not easy to interpret the morphology of these Elsterian channels in the terms of fluvial erosion or of scouring by the base of an ice sheet. It has been assumed by Cameron *et al.* (1987) that the features were most likely to have been eroded subglacially, under very high hydrostatic pressure by outbursts of meltwater beneath a continuous cover of land ice. The filling processes started under the cover of the ice, with slumping of moraine and the deposition of glaciofluvial sediments. After the ice had retreated from the area, thick accumulations of glaciolacustrine sediments, locally overlain by fluvial deposits, infilled most of the Elsterian valleys. Similar valleys and sedimentary sequences are well known from the onshore area of the Netherlands and of Lower Saxony, Germany, where they have been systematically mapped in the course of the search for groundwater resources (Kuster & Meyer 1979; Ehlers *et al.* 1984). The valley systems and the infill record the earliest extension of the inland ice into both the southern North Sea and its hinterland. Together with the ice-pushed deposits, they demonstrate that there was a continuous cover of inland ice from eastern England across the Southern Bight to the Netherlands and to Germany during Elsterian times (figure 3).

Elsewhere, beyond the offshore extent of land ice, smaller-scale valleys in the central and northern North Sea and the English Channel may have been formed by catastrophic proglacial fluvial events (Smith 1985; Long & Stoker 1986*a*) and are filled by postglacial marine deposits and by glaciomarine sediments from the succeeding glaciation.

2.3.2. *Holsteinian interglacial period*

By the onset of the Holsteinian (Hoxnian) interglacial period, most of the Elsterian valleys of the southern North Sea had been totally filled by non-marine sediments. The few remaining depressions contain an additional component of marine sediments from the Holsteinian transgression, which extended across most of the North Sea area and locally smoothed the pre-existing relief.

Holsteinian marine deposits are rarely preserved in the southern U.K. sector of the North Sea (Cameron *et al.* 1987), but borehole BH81/52A recovered 14 m of shallow-water marine clay of interglacial aspect, believed to be Holsteinian and comparable with Hoxnian dated deposits (Egmond Ground Formation) cropping out in Silver Pit (Balson & Cameron 1985). Further east, in the Dutch sector, Holsteinian interglacial deposits (Egmond Ground Formation) are represented by sparsely shelly very fine-, fine- and medium-grained sands with thin beds of silt and clay (Laban *et al.* 1984). Outside the former valleys these deposits are less than 25 m thick.

Examination of the molluscs and microfauna of the Holsteinian sediments in the Danish North Sea sector and in the German onshore area (Grahle 1939; Woszidlow 1962; Lange 1962; Knudsen 1980) as well as palynological studies (Menke 1970; Müller 1974) indicate an increasing amelioration of the water temperature during this interglacial period. The fauna and flora indicate that the arctic climate of the early Holsteinian gave way to boreal conditions and eventually to a temperate climate with water temperatures in the southern North Sea similar to those of the present day.

Electron spin resonance (ESR) spectroscopy of 27 samples of aragonitic mollusc shells from the Hamburg area, from the lower Elbe river valley, and from Cuxhaven on the German North Sea coast (Linke *et al.* 1985) have yielded three groups of ages for the different localities with average ages of 195 ± 25 ka BP, 223 ± 25 ka BP and 218 ± 25 ka BP; these ages indicate correlation with stage 7 of the oxygen-isotope deep-sea record (Shackleton & Opdyke 1973). On the basis of three uranium–thorium dates, selected from a total of seven dates, Sarnthein *et al.* (1986) concluded that the Holsteinian deposits at Wacken, Schleswig–Holstein, are older than 350–370 ka. Therefore, these authors correlate the Holsteinian interglacial period with $\delta^{18}O$ stage 11 on the CARTUNE and SPECMAP scale (Herterich & Sarnthein 1984). Also outside Germany there is no agreement on a correlation between dated Holsteinian (Hoxnian) deposits and the deep-sea record.

On the margins of the southern North Sea, Holsteinian marine deposits occur in marine terraces 25 m above sea level in East Anglia (Mitchell 1977), at an elevation of 10–12 m near Sangatte on the French coast (Sommé 1979) and in Belgium (Paepe & Baeteman 1979). In The Netherlands, the surface of marine Holsteinian deposits occurs at −25 to −40 m (van Staalduinen 1977) and in northern Germany they fill a '*Förde*'-like system to an elevation of *ca.* −20 to −30 m (Ehlers *et al.* 1984; Linke 1986). The difference in elevation can perhaps be attributed to post-Holsteinian isostatic processes.

2.3.3. *Saalian glacial period*

At the maximum extent of the Saalian glaciation, an extensive ice-sheet covered the entire lowland area of Lower Saxony, Germany (Meyer 1983) and parts of the adjacent mountainous regions to the south. The ice-thrusted ridges of Itterbeck-Uelsen, Emsland, and of Krefeld–Kleve at the Lower Rhine River, mark the southern limit of the ice sheet in northwestern Germany (figure 3). In The Netherlands, this ice advance formed the ice-pushed ridges of Nijmegen, Arnhem and Rhenen and formed deep glacial basins in the Amsterdam–Haarlem area. In the Dutch North Sea sector, till has been found up to 40 km off the coast on the Terschelling Bank sheet, and an ice-marginal valley and ice-pushed structures have been

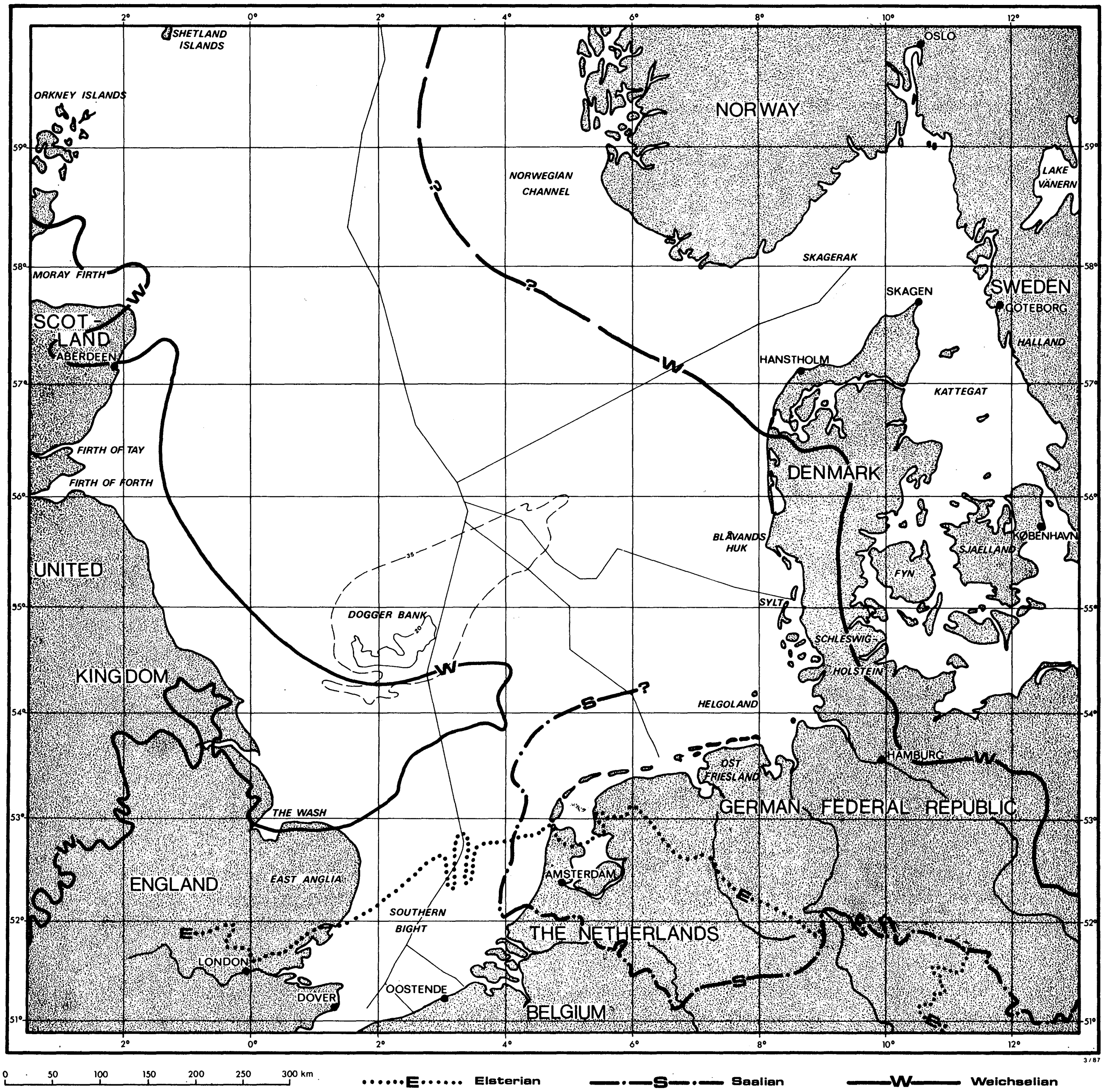

FIGURE 3. Palaeogeographic reconstruction of the ice margins of the Elsterian (Anglian), Saalian (Wolstonian), and Weichselian (Devensian) glacial periods in the North Sea and in the adjacent onshore areas.

detected in the northwestern Flemish Bight sheet (Laban *et al.* 1984). The available evidence suggests that the Saalian ice has not extended west of 4° E into the Indefatigable or Silver Well sheets (figure 3). Saalian proglacial deposits (Cleaver Bank Formation) and periglacial deposits (Tea Kettle Hole Formation) occur on the eastern halves of both sheets (Cameron *et al.* 1986; Jeffery *et al.* 1988).

The Tea Kettle Hole Formation consists of well-sorted, very fine- or fine-grained, and only sparsely micaceous wind-blown sands up to 6 m thick. The Cleaver Bank Formation consists of proglacial silty clays with silt and sand laminae and locally (especially on Indefatigable) fluvioglacial, very fine- to fine-grained, micaceous outwash sands with beds of silt and clay, which were deposited beyond the ice front.

Opposing views have been expressed by Straw (1983), Sumbler (1983), and Rose (1987) as to whether a contemporary ice sheet covered eastern England. Till-like sediments of Saalian age have neither been sampled in the U.K. sector of the North Sea nor in the western half of the Dutch sector. The offshore evidence in the Dutch sector indicates that periglacial conditions prevailed over most of the southern North Sea during this period. Therefore, it seems likely that there was no connection between the Scandinavian and possible Scottish ice sheets across the Central or northern North Sea during the Saalian glaciation (figure 3).

2.3.4. *Eemian interglacial period*

Marine sediments of the Eem Formation (115–125 ka BP) have been identified at many sites in the southern North Sea. In the British sector, the Eem Formation comprises up to 20 m of intertidal and shallow marine sands and clays. The sediments become more fully marine towards the east; in the Dutch sector, the formation is composed of fine- or medium-grained, locally gravelly sands with a markedly higher shell content than the deposits of the Holsteinian and Holocene transgressions (Cameron *et al.* 1988). Fully marine Eemian deposits occur as the basal fill of some of the Saalian valleys in the central and northern North Sea.

No marine beds of the E1 and E2 pollen zones have so far been recorded from the southern North Sea (Jelgersma 1979), but marine deposition has been demonstrated for the E3 to E6 pollen zones by Oele & Schüttenhelm (1979), and offshore from Sylt and Borkum on the German North Sea coast (Ludwig *et al.* 1981). The investigations of the molluscan and microfaunal assemblages (Lafrenz 1963; Hinsch 1985; Knudsen 1985*a*,*b*) and of the pollen assemblages (Menke 1985) of the deposits have indicated climatic amelioration during Eemian transgression from subarctic or high boreal conditions towards temperatures which were at least as warm as they are at present in the southern North Sea.

In eastern Britain, marine deposits of the Eemian interglacial *ca.* 7 m above present sea level occur in the inner part of the Thames estuary and around the Wash, and at +2 m in the seaward part of the Humber estuary and in East Anglia (Mitchell 1977; Jardine 1979). In Belgium they occur at an average depth of −5 m below the western coastal plain (Paepe & Baeteman 1979). The highest elevation of the surface of marine Eemian deposits is at −8 m in the western part of the Netherlands and at −13 m in the Groningen area (Jelgersma 1979; Roeleveld 1974). Along the German North Sea coast the surface lies at −9 to −7 m in Lower Saxony and at −5 m in western Schleswig–Holstein. The Eemian coastline intersects with the present North Sea coast at Blåvands Huk, Denmark. The range of elevations of marine Eemian deposits shows a similar pattern to the Holsteinian units; this observation suggests that both have been influenced by post-Eemian isostatic processes.

2.3.5. *Weichselian glacial period*

Climatic deterioration towards fully glacial conditions caused regional sea level in the North Sea to fall to at least 110 m below present by late Weichselian times (Jansen *et al.* 1979). Local effects of glacial depression and rebound have not been studied so far. The uppermost Eemian sediments in the Southern Bight of the North Sea are widely overlain by grey-brown, brackish-marine to freshwater silty clays with silt and very fine sand laminae (Brown Bank Formation). The major part of these sediments has been deposited in a lagoonal environment during the early stages of regression. The deposits are extensively bioturbated and locally cryoturbated (Cameron *et al.* 1988). According to pollen analyses, sedimentation occurred in the Dutch pollen zone EW 1A, which ranges from Late Eemian to Early Weichselian times.

In the Dutch sector, the brackish-marine beds are overlain by lacustrine clays, deposited as the sea fell to below −40 m in the area. Glaciomarine clays, deposited in front of the ice in the Dogger Bank area, are now at −55 m (Jeffery *et al.* 1988). Probably there existed at one time a restricted and elongated marine embayment over a glacially depressed part of the North Sea just in front of the British Weichselian land ice. This embayment extended from the northern North Sea as far south as SE of the Dogger Bank.

A blanket deposit of Weichselian till (Bolders Bank Formation) extends northeastwards from the coast of East Anglia into the northwestern part of Indefatigable sheet (Cameron *et al.* 1988) and contains boulders derived mainly from the Upper Palaeozoic and Mesozoic rocks of eastern England (figure 3). Glaciolacustrine clays and diamictons occur below and east of the southern Dogger Bank (Cameron *et al.* 1986; Jeffrey *et al.* 1988). Along the eastern coast of the North Sea, the Weichselian end-moraines run through eastern Schleswig-Holstein, Germany, and southern Jutland, in a north–south direction. At the Limfjord, Denmark, the moraines turn to the west and trace into the North Sea; their offshore continuation is uncertain (figure 3). Offshore evidence, however, suggests that there was no connection between the British and the Scandinavian ice sheets across the southern North Sea during the Weichselian glacial period (Cameron *et al.* 1988).

South of the maximum extent of the ice sheet, terrestrial and fluvial sedimentation took place in vast tracts of the southern North Sea (Cameron *et al.* 1988). Aeolian fine-grained sands (Twente Formation) are preserved locally on the Flemish Bight and Indefatigable sheets, and in the German sector of the North Sea. Fluvioglacial micaceous, very fine- or fine-grained Weichselian sands with intercalations of silt and clay occur adjacent to the till margin on Indefatigable sheet. Late Weichselian subglacial valleys in the north of Indefatigable have been partly or completely infilled by poorly sorted, gravelly coarse sands overlain by very soft sandy lacustrine clay.

During the Weichselian the rivers discharged into the central North Sea. The most important drainage system of the north German hinterland was the so-called 'Elbe–Urstromtal', which acted as an ice-marginal valley during the Weichselian glacial maximum. Figge (1980) has mapped the course of this 30–40 km wide valley system on the basis of Boomer profiling between Helgoland and the White Bank area. During the Weichselian late-glacial period, the central North Sea, comprised a shallow brackish marine sea, with a cover of sea ice, surrounded by flat periglacial tundra dissected by braided rivers downstream of the Middle and North European rivers (Stoker & Long 1984). As the temperature and sea level rose, sea-ice keels became smaller and the sediments at the bottom of the shallow seas ceased to be reworked; this resulted in the deposition of acoustically well-layered formations. Dinoflagellate cyst assemblages indicate that sea ice was absent from this area during the Bølling interstadial (Long *et al.* 1986), during which there was an influx of warmer Atlantic waters. Low salinity values (based on foraminiferal and molluscan assemblages) and evidence of rapid sedimentation together with possible water stratification suggest significant input continued from meltwater sources. During the Younger Dryas, the connection with the North Atlantic remained open and there was only limited pack-ice. These processes are summarized in figure 4. The onset

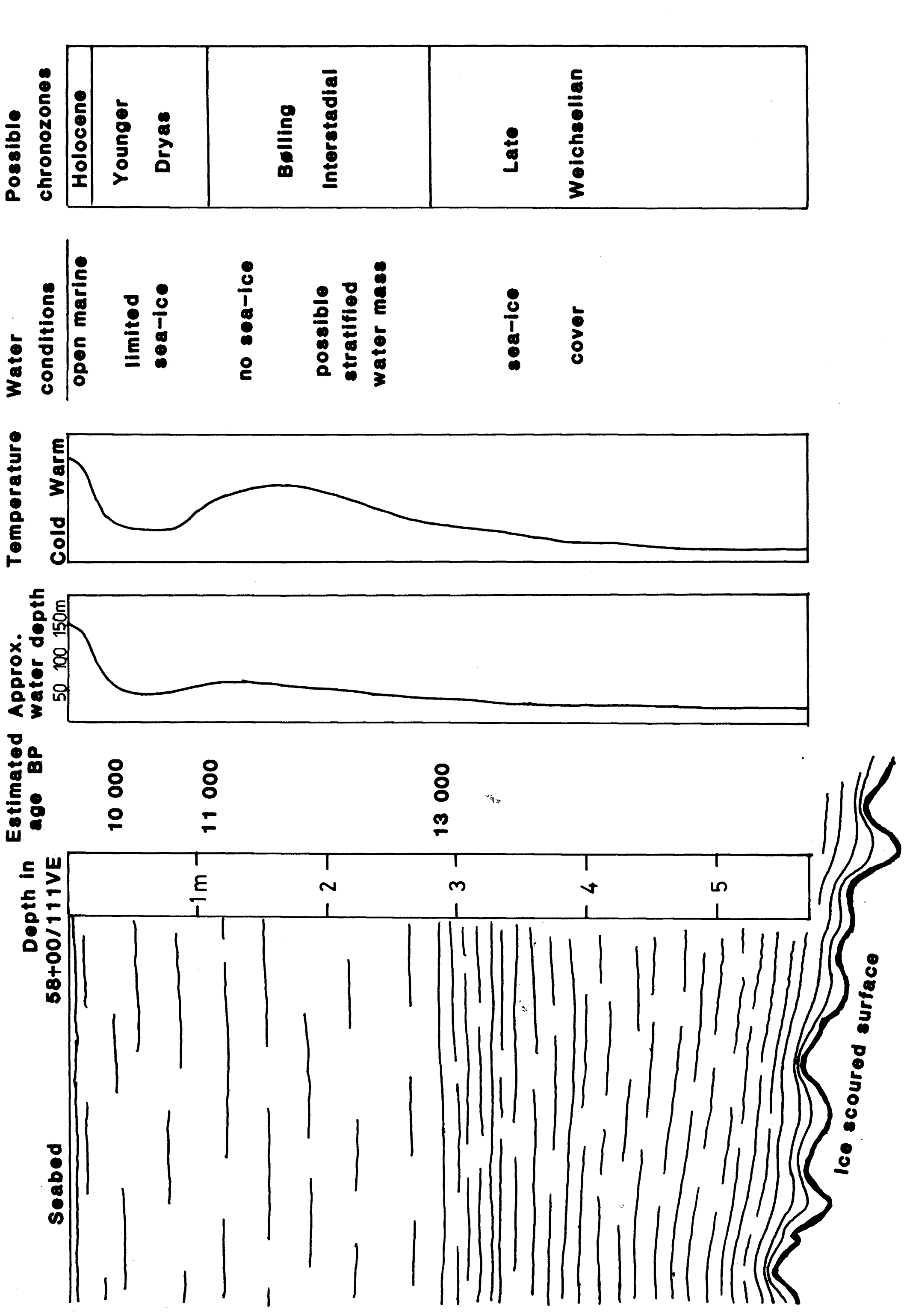

FIGURE 4. Estimated environmental conditions in the central North Sea for the Late Weichselian to Holocene periods, based on vibrocore 58+00/111VE from the Witch Ground Basin, with schematic seismic section. (Based on Long *et al.* 1986.)

of the Holocene is indicated by the sudden rise in water depths and the near cessation of sedimentation in the central North Sea.

The terrestrial parts were exposed to periglacial conditions during the Weichselian glacial period. Evidence of periglacial activity is represented by segregated ground-ice fabrics (Derbyshire *et al.* 1985), by ice-wedge structures (Streif 1985) and asymmetric valley slumping (Long & Stoker 1986*b*). Similar exposure of the sea bed and similar processes are believed to have occurred in the Elsterian and Saalian glacial periods.

2.3.6. *Holocene*

The earliest Holocene brackish-marine incursion into the southern North Sea may have occurred as early as 10 ka BP (Eisma *et al.* 1981). With continuing rise in sea level, tidal-flat sedimentation became more widespread between 9 ka and 8 ka BP and fully marine conditions spread out over most of the Southern Bight after 7 ka BP (Eisma *et al.* 1981). The Holocene sediments in the Southern Bight and in the German Bight are generally less than 5–15 m thick. On the basis of foraminiferan assemblages, Uffenorde (1982) reconstructed the facies zonation of these deposits. Maximum thicknesses of 30 m of Holocene sediment occur in the linear sand ridges and in sea bed depressions which have been partly filled by fine sandy and muddy deposits.

From the 110 m rise of the North Sea in the Weichselian late-glacial and Holocene periods, only the uppermost 46 m can be reconstructed on the basis of reliable radiocarbon dates. These dates have been obtained from basal peats, resting on Pleistocene deposits and which are overlain in turn by Holocene brackish or marine sediments. Sequences of up to 35 m of marine sand, tidal-channel fill, shoal and beach sediments occur in the barrier system on the west coast of Belgium and the Netherlands and in the West Frisian, the East Frisian, and North Frisian Islands. Thick clastic sequences of intertidal and subtidal sandy sediments were deposited in the seaward areas of the tidal flats. In the landward areas of the tidal flats and in the subsoil of the coastal marshes, peat layers are intercalated in tidal, brackish, and lagoonal deposits. According to Streif (1985), these layers have been deposited since 6.5 ka BP and demonstrate phases of retardation in the rise of sea level from 4.8 to 4.2 ka BP and from 3.3 to 2.3 ka BP. Fossil soils on brackish sediments and horizons of decomposition in the peats indicate a temporary lowering of the water level at about 2.7 ka BP, and at 2 ka BP.

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Discussion

R. Paepe (*Belgian Geological Survey, Brussels, Belgium*). How does Dr Streif explain that gullies on the Ostend Sheet, south of the Flemish Bight sheet, are less deep (30 m maximum) than in the area he studied (300 m depth)?

H. Streif. The channels seen in the Indefatigable map area are the largest observed in the North Sea and are up to 400 m deep; elsewhere channels of 100 m or more are normally the maximum. So an exceptional reason may need to be found for the Indefatigable area rather than elsewhere. The dramatic difference in channel depth over such a short distance may also be related to differing methods of formation.

If the most widely held view of channel formation is taken (subglacial erosion by meltwater) then it could be assumed that the large channels in the Indefatigable area represent the area with the maximum volumes of meltwater (i.e. near the glacier front) and the much smaller channels in the Ostend area may represent proglacial fluvial erosion by the release of the meltwater. However, if they too were formed by subglacial erosion, then it might be assumed that ice covered the Ostend area for only a short period of time, before channels deeper than 30 m could develop, but this seems particularly unlikely as there is no other evidence for glacial cover.

Such methods of channel formation assume that the channels observed in the Ostend and Indefatigable map areas are related. However, the usual explanation for the channels in the Ostend area is fluvial erosion during periods of low sea level. A proto-Thames channel of about 20 m depth has been identified in the U.K. sector of the Ostend map area (P. Balson, personal communication).