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The Late Quaternary History of Denmark

The Weichselian Icesheets and Land/Sea Configuration in the Late Pleistocene and Holocene

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INTRODUCTION

Danish geologists have studied Late Quaternary stratigraphy for many years. Compared with our Scandinavian neighbours Denmark has an advantage in that the country covers part of the North Sea depression, in the central part of which some 1000 m of quaternary sediments have accumulated. The country also lies in the submarginal zone of the areas covered by icesheets during the Quaternary. The northern and eastern parts of Denmark thus contain up to 200 m of quaternary deposits laid down during and after the last interglacial, the Eemian. Southwestern Denmark, beyond the limits of glacial advance, has not been covered with ice within the last 100,000 years.

My aim will be to locate the ice masses during the last glacial, the Weichselian. It will emerge that these ice masses were only present for relatively short periods. The changing land/sea configurations for this period will show some features which also characterize the subsequent Holocene period. In the postglacial the raised temperatures led to the re-establishment of the marine fauna known from the last interglacial. A global eustatic rise in sea level took place in the Holocene, just as in the Eemian interglacial.

In advance of the following sketch of the stages of palaeogeographic development, I must state that not all Danish quaternary geologists share all my views, and there are also differences of view among colleagues in neighbouring countries. This is due to the poor dating information hitherto available for the earlier part of the period – which cannot be covered by radiocarbon dating. In the last few years, however, we have managed to date the earlier deposits by other means, such as thermoluminescence (TL) and amino acid analyses. In combination with traditional lithostratigraphic and biostratigraphic methods, these datings have allowed the chronological fixing of the various horizons which has so far been lacking. A short review of this discussion can be found in the Uppsala Symposium, "Ten Years of Nordic Till Research" (Petersen 1984a).

For the late Pleistocene the discussion will be based on certain key localities in Denmark. These are shown in the review of late Pleistocene conditions (Petersen 1984a, fig. 2). According to position, they will in the following be described as representatives of the northern, southeastern and southwestern parts of Denmark. For the exact locations see fig. 1.

LATE PLEISTOCENE

The Eemian

Eemian interglacial deposits occur at sites in southern Denmark; both in the west, the classic Eemian occurrences in the South Fyn Archipelago (Madsen et al 1908) with a rich fauna indicating shallow marine conditions; and in the east, sites in south Sjælland and Møn having a deeper water fauna characterized by the snail *Turritella communis* (Ødum 1933). It was biostratigraphically difficult to demonstrate the contemporaneity of these deposits, as the faunal elements are so different – *Turritella communis*, for example, was absent from the southwest Danish Baltic regions in the Eemian.

Also available were the very important deep borings Skærumhede I and II (Jessen et al 1910; Bahnson et al 1974), through the very thick layers of marine sediments in Vendsyssel, northern Jutland. *Turritella communis* was indeed present, but it was difficult to determine whether the marine sequence did in fact include the Eemian.

Recent stratigraphic studies of foraminifera from Skærumhede I and II and the island of Anholt in the Kattegat have demonstrated that a deeper facies of the Eemian Sea is found from the area around Anholt, and

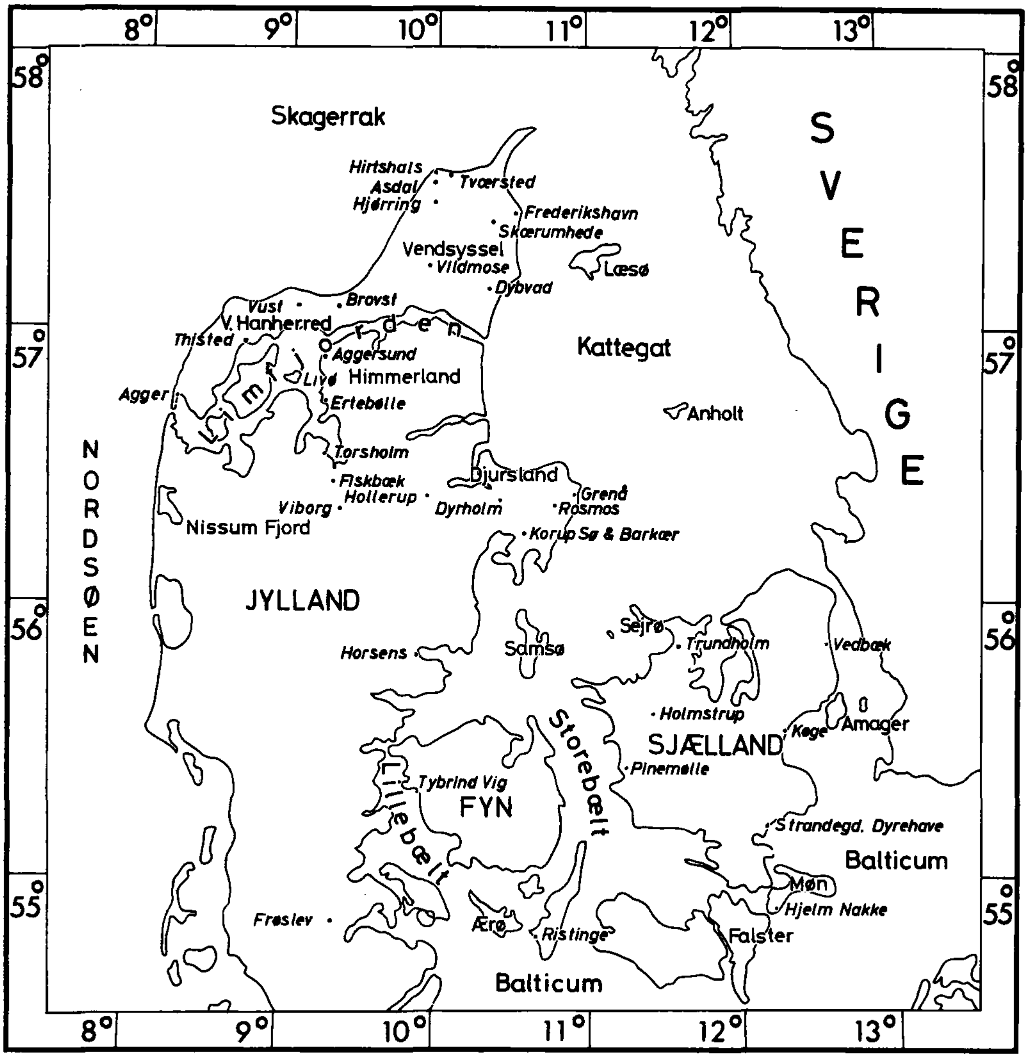

Fig. 1. Map showing places and coastal waters named in the text.

across Vendsyssel to the Skagerrak (Knudsen and Lykke-Andersen 1982). A long series of amino acid datings, carried out in the USA by Gifford Miller in co-operation with Jan Mangerud of Norway (Miller and Mangerud in press) has furthermore shown that the southern Danish locations discussed are indeed contemporary – from the Eemian – and also that the east Danish sediments (dated on *Turritella communis*, the same species found in the deeper part of the Skærumhede sequence in Vendsyssel) can be correlated with these.

The conclusion of this is that in the Eemian there was a palaeo-Kattegat of greater extent than at present, in that it covered large parts of Vendsyssel as well as the western part of the Baltic, with a littoral fauna (Konradi 1976) in the area south of Fyn and southeast Jutland, and with a deeper water fauna in south Sjælland and the Islands (Petersen and Konradi 1974).

Many studies of vegetational development in Jutland (Jessen and Milthers 1928; Andersen 1975) have shown that there are many lacustrine Eemian localities, from southern Jutland as far as Hollerup in the north. This area was therefore dry land in the last interglacial (fig. 2).

In the southern coastal zone of West Jutland marine deposits of Eemian age have been found, and south of the German border there were true fiords stretching in to the east. No marine connection has, however, been

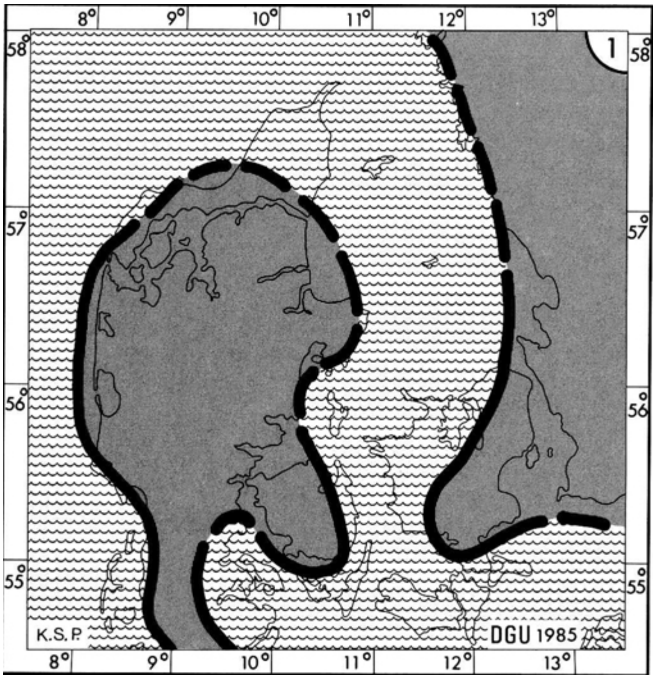

Fig. 2. Land-sea configuration in the Eemian. First scenario in the palaeogeographic suite of 6 for the Pleistocene part of the Late Quaternary.

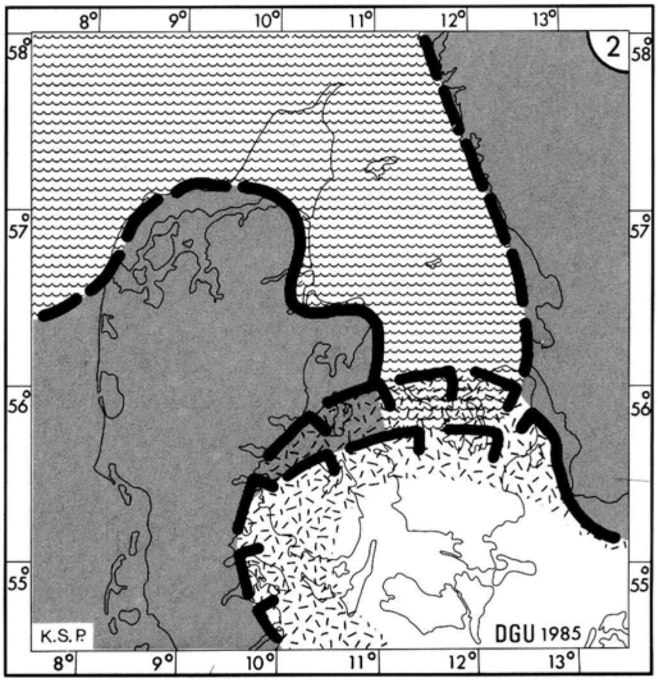

Fig. 3. Land-sea-ice configuration in the Early Weichselian. Second scenario, older than 50,000 BP.

demonstrated between the Baltic and the North Sea across the Jutland peninsula in the Eemian (Königsson 1979).

The Early Weichselian

From the Eemian-Weichselian transition, continuity in the marine deposits is seen only in the northernmost part of Denmark, namely Vendsyssel. In this area deep water formations continue, characterized by the following mollusc succession: *Turritella communis* and *Abra nitida* going over into the Arctic *Turritella erosa*. Within the *Turritella erosa* zone (Bahnson et al 1974) there are ice-transported stones, a phenomenon not unknown in Arctic regions when icebergs break off glaciers.

Norway and Sweden provide evidence of glacial advance during an early part of the Weichselian, dating to older than 50,000 years. In Norway this reaches the coastal zone (Mangerud 1983). In Sweden, however, ice cover has only been demonstrated in the far north (Lundqvist 1983); further south in the east Baltic region opinions differ as to the extent of ice cover in this early phase. Andersen et al. (1982) sum up this discussion by saying that evidence of cold phases of early Weichselian date with evidence of glacial advance is found in several places, but that it is difficult to pinpoint these in time due to a lack of good dates. In northern Poland, however, three till deposits of Weichselian age have been recognized (Mojski 1982, fig. 9), the oldest of which has been dated by C-14 and thermoluminescence to older than 50,000 years (Drozdowski 1980).

It has been suggested (Andersen et al. 1982) that till-like glaciomarine deposits at Hirtshals (Lykke-Andersen 1981) indicate glacial advance. All that is visible, however, is a deposit comparable to the drop till sequence in the Skærumhede boring (Bahnson et al 1974).

Recent examination of material from borings near Frederikshavn also shows continuous *marine* sedimentation in the time period (Knudsen 1984).

Regardless of the differing opinions concerning the extent of ice cover in northern Denmark, an Old Baltic ice sheet has been demonstrated lithologically between Eemian deposits and later Weichselian moraines at several sites in southern Denmark. These are: Strandegård Dyrehave (Petersen and Konradi 1974), Hjelm Nakke (Berthelsen et al 1977) and Ristinge (Sjørring et al 1982). The site of Holmstrup on Sjælland (Petersen

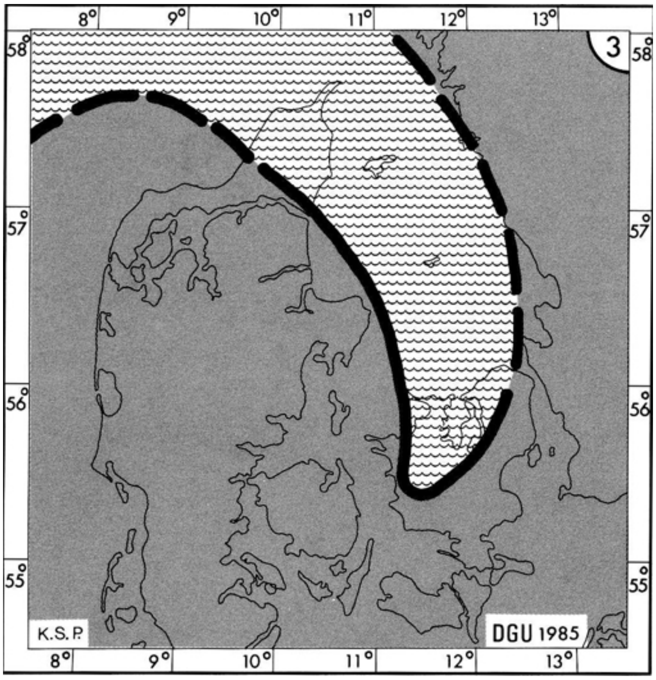

Fig. 4. Land-sea configuration in the Middle Weichselian. Third scenario, 45,000 – 35,000 BP.

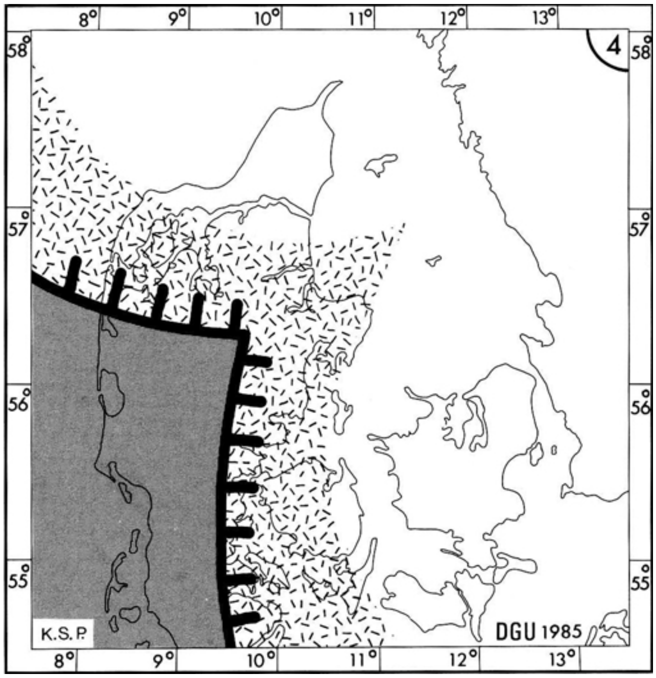

Fig. 5. Land-sea-ice configuration in the Late Middle Weichselian. Fourth scenario, 22,000 – 16,000 BP.

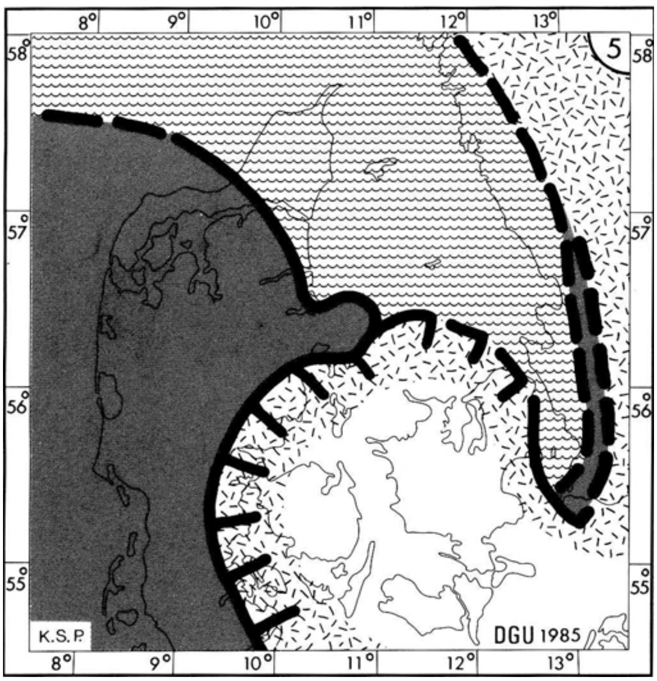

Fig. 6. Land-sea-ice configuration in the Late Middle Weichselian. Fifth scenario, 16,000 – 13,000 BP.

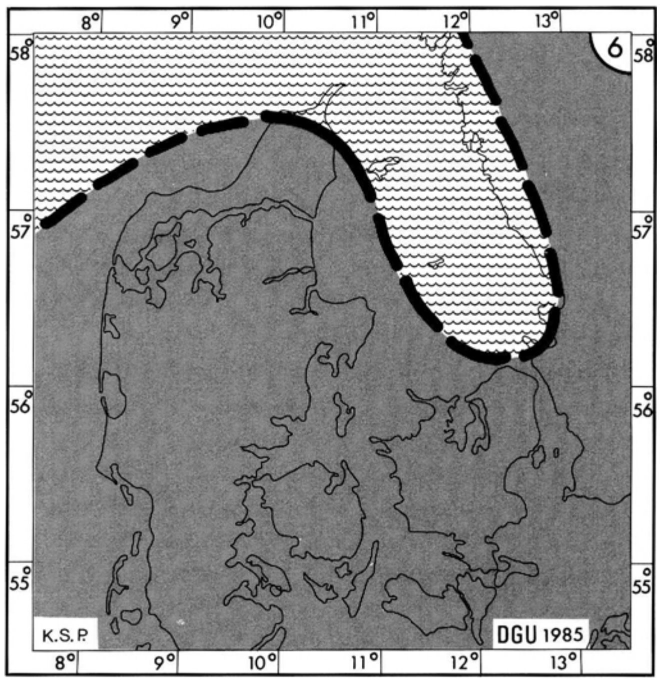

Fig. 7. Land-sea configuration in the Late Weichselian. Sixth scenario, around 11,000 BP.

and Buch 1974) has a Baltic moraine at the base of the quaternary succession, overlain by a marine Arctic sequence of Middle Weichselian age.

The suggestion of a Baltic ice sheet in the Early Weichselian is also supported by a thermoluminescence date of 75,000 BP from meltwater deposits overlying the Eemian interglacial diatom site at Hollerup. This is also the site of the oldest safe evidence of human population in Denmark (Møhl-Hansen 1955). Thermoluminescence dates from the lake sediments and the overlying meltwater deposits are 87,600, 80,000 and 74,800 years respectively (Kronborg 1982, table 1).

The deposition of this meltwater sand could therefore very well have occurred in connection with an Old Baltic glacial advance.

An alluvial cone at Frøslev in Southern Jutland (Kolstrup and Havemann 1984) contains a buried soil horizon with *Juniperus* dated to about 50,000 years. The alluvial cone, which was earlier believed to have been formed in connection with Late Weichselian ice sheets, is thus more likely to have been formed during an Early Weichselian glacial advance (fig. 3) resting on Eemian deposits.

All this suggests a Weichselian landscape before 50,000 years BP with an icesheet in southern Denmark. Meltwater from it was affecting parts of Jutland, and icebergs were breaking off into the palaeo-Kattegat which still covered Vendsyssel. No marine deposits have been documented in southwestern Jutland, and it must be assumed that the sea level had undergone a eustatic fall so that large areas towards the North Sea were uncovered.

The Middle Weichselian

Marine deposits dating from the period 45,000 – 35,000 BP are found at Hirtshals (Lykke-Andersen 1981), which are correlated with the Skærumhede sequence in eastern Vendsyssel. The marine deposits mentioned above at Holmstrup on Sjælland (Petersen and Buch 1974) can be biostratigraphically correlated (by means of foraminifera) with these North Jutland sites. Amino acid dates on *Macoma calcarea* also correspond. This macrofossil characterizes the deposits at Holmstrup, and have been used to name the uppermost zone in the Skærumhede II cold sequence. The extent of the Older Yoldia Clay has also been established by Anne-Lise Lykke-Andersen, on the basis of recent borings in the Sjælland region (1979, fig. 3). Lykke-Andersen's work shows that the Older Yoldia Clay on Sjælland does not overlie Eemian marine deposits; this supports the idea of an Early Weichselian ice sheet in these areas which truncated the earlier Eemian marine deposits.

The conclusion from this is that a palaeo-Kattegat continued to exist, stretching down from the north to cover northwestern Sjælland (fig. 4).

C-14 dated peats on Sejrø, aged to around 36,000 BP (Houmark-Nielsen and Kolstrup 1981), indicate that Denmark was free of ice at this time. Lake sediments from the same deposits on Sejrø have been TL dated to 35,200 BP (Kronborg 1982). The meltwater deposits overlying these lake sediments have furthermore been dated to 31,200 BP, but it is regarded as certain that Denmark was not covered by ice at this time. This is because the dates of many finds of mammoths in this period – running up to 21,000 BP – make it probable that Denmark and the adjacent areas to the north and east were free of ice, and formed a great "mammoth steppe" (Petersen 1984a).

The Late Middle Weichselian

The marine sequence at Skærumhede in northern Jutland, which we have been able to follow from the Eemian and which has been central to interpretations of the palaeo-Kattegat, reaches its conclusion during the maximal advance of the Weichselian ice sheet. Only southwestern Jutland remained free of ice, leading to the formation of the large heath areas there (fig. 5).

The chronology of the glacial movements is that a Norwegian ice sheet is replaced by a so-called Northeast ice sheet, which is followed by a final Late Baltic advance. The last-named will be discussed later, in connection with recent marine formations in northern Denmark.

Thermoluminescence determinations (Kronborg 1983) on meltwater deposits from Livø and Viborg have dated the start of the spread of ice in the Late Middle Weichselian to between 22,000 and 20,000 BP. In the period through to 15,000 BP, when C-14 dates of marine deposits in north Jutland show the ice to be melting, the land area of Denmark was thus limited to the areas beyond the edge of the ice and further west in the present North Sea.

Late Middle Weichselian – Late Weichselian

During the final phase of the Weichselian, consisting of the Late Middle Weichselian and the Late Weichselian (from 13,000 BP), the northern part of Denmark was free of ice, but large areas of the northeast were covered by an Arctic Sea, the Younger Yoldia Sea. The deposits of this sea are well dated by C-14 (Krog and Tauber 1974), and the molluscan fauna is so well documented that shallow and deep water deposits can be fitted into a scheme based on these dates. This scheme shows that the maximum marine transgression was reached in Vendsyssel between 14,000 and 13,000 BP (Petersen 1984b).

Deposits from the Younger Yoldia Sea are known from the island of Læsø in the Kattegat (Michelsen 1967), with C-14 dates of around 13,000 BP. The extent of the Younger Yoldia Clay further south has been documented by marine geological studies (Konradi pers. comm.), which demonstrate that it extended north of Sjælland and east of the Djursland peninsula.

The east Jutland ice limit (line D) is dated to 13,240 +760/÷690 BP (K-3697B), the date being on a mammoth tusk found in the extramarginal formations at Rosmos on Djursland. Thus the Late Baltic glacial advance, represented by the east Jutland ice limit and a glacial edge breaking up into icebergs east of the Djursland peninsula, may have reached the later palaeo-Kattegat (Petersen 1984b, p. 67) (fig. 6).

The Late Weichselian

The ice retreat from southern Denmark took place before 13,000 BP. The existence of a new mammoth steppe at this time is possible, because a mammoth from southern Sweden has been dated to 13,200 BP. The Lockarp mammoth (Lagerlund et al 1983) should date the ice limit at Hallandsåsen (Mörner 1969). It is not likely that an ice-cover should have lasted after 13,000 BP in Denmark according to investigations by Kolstrup (1982) and Ussinger (1978) on Møn and Bornholm respectively.

The late glacial environment was very rich, over and above the presence of mammoths and the Arctic sea, as investigations from Vendsyssel show. The old find of a polar bear from Asdal, north of Hjørring, has been dated to 11,100 BP (Aaris-Sørensen and Petersen 1984). The polar bear was thus present contemporary with brown bear, desman (Bondesen and Lykke-Andersen 1978) and some of the first traces of human occupation in Denmark after the glacial (Krog 1978). The first Danish site is known from Jels representing the Hamburgian Culture (Holm and Rieck 1983).

By 11,000 BP there are no further traces on dry land of marine deposits of the Younger Yoldia Sea, and since 13,000 BP the littoral molluscan fauna had become dominated by boreal species, the so-called *Zirphaea* fauna. The earliest dated find of *Zirphaea crispata* is as early as 12,700 BP, i.e. belonging to the Bølling, the first warm phase following the Middle Weichselian. The start of this is placed at 13,000 BP (Mangerud et al. 1974). Other boreal species can be mentioned from the Late Weichselian, such as *Cyprina islandica*, *Mytilus edulis*, *Macoma balthica* and *Lacuna vincta*. A similar development, with a distinct change from an arctic to an arctic-boreal molluscan fauna, was taking place on the Swedish Kattegat coast (Berglund and Mörner 1983). Borings in the present Kattegat have yielded a succession of foraminifera showing a change from a purely arctic composition to an association similar to that known from the Holocene (Konradi pers. comm.) (fig. 7).

Late Weichselian – Holocene

The continental period in Denmark, except for a part of the Kattegat, is defined as beginning at the end of the Allerød interstadial (11,000 BP), lasting into the Holocene (7500 BP), when the early Atlantic transgression created the archipelago that comprises Denmark today. These developments will be discussed below.

HOLOCENE

Isostasy and Eustasy

The development of land-sea configurations in the Holocene is closely connected with the events of the preceding 100,000 years.

Far into our own epoch the depression of the earth's surface by the Late Middle Weichselian ice masses has resulted in isostatic uplift. The area of this uplift fits very closely with the area covered by the last maximum of glacial advance (Mörner 1979).

Neotectonic movements, which can be linked to larger phenomena (such as the Fennoscandian Border-zone near Læsø: (Hansen 1980); and generally (Lykke-Andersen 1979)), cannot be excluded in certain areas; nor can movements connected with both the northern and southern Danish salt structures, e.g. the Thisted structure (Hansen and Håkansson 1980).

In northern Denmark the Older Yoldia Clay and interglacial marine clay of Eemian date have a thickness of up to 150 m. The highest part of this is found at the –25m contour. The Younger Yoldia Clay is found up to +60m, while the Holocene marine deposits are found up to 13 m above sea level in northern Jutland.

The demonstration of sea level changes through this long time span, resulting from the interplay of isostatic and eustatic factors, could be approached through an evaluation of the faunal composition and its variations at different depths. This is suggested in studies of marine deposits from the Weichselian and Holocene in northern Jutland (Petersen 1984b, 1985a).

On the basis of data from the Kattegat compared with that from the rest of western Europe, Mörner (1980, fig. 8) has established a regional northwest European eustatic curve.

It can be seen from this that at 20,000 BP, when the Scandinavian ice sheet reached its line of maximum advance in Jutland, sea level had fallen to a point near 90 m below present levels.

Through to around 10,000 BP (the beginning of the Holocene), there was a eustatic rise in sea level of 60 m. It is this rise which, in conjunction with the depressing of northern Denmark under the weight of ice, allowed the deposits of the Younger Yoldia Sea to be laid down in the period 15,000 – 11,000 BP. Shorelines at +60 m were formed in Vendsyssel between 14,000 and 13,000 BP (Petersen 1984b).

In the millennia from 13,000 to 10,000 isostatic uplift of the land *predominates*, because at the same time there is a diminution in the eustatic rise.

Shorelines were formed at ever lower levels, the latest dated example within the present Danish area being at 11,000 BP, the end of the Allerød.

In the periods of the Younger Dryas and the Preboreal there are no dated marine deposits in Denmark. This period is often described as the continental period. The greater extent of dry land is shown by the innumerable finds of terrestrial and lacustrine deposits under the seas round Denmark (Krog 1973). Archaeological data in the form of cultural materials from the seabed add to this (Fischer and Sørensen 1983).

The Boreal-Early Atlantic Transgression

The first demonstration of the rise in sea level in the Holocene was in the Great Belt region, using pollen analytical and radiocarbon datings (Krog 1960, 1973). A transgression to –30 m level can be dated to around 8000 BP. Later investigations in the same area have established the steepness of the eustatic sea level curve (Petersen 1978, fig. 5). It emerges that there was a 20 m rise in sea level in the Late Boreal and Early Atlantic periods.

It has also been possible to establish an Early Atlantic transgression to a height of –25 m at around 7800 BP in the Limfiord region in northern Denmark. It has furthermore been possible to establish the steepness of the sea level curve by considering dates of marine deposits in the immediate vicinity laid down in shallow water and above present sea level (Petersen 1981, fig. 3).

The results achieved support to that part of Mörner's curve covering eustatic fluctuations since 9000 BP. The rise is particularly marked in the first two millennia, up to 7000 BP.

It is calculated from the Limfiord data that sea level rise was 28 m in 880 C-14 years, or 32 m per C-14 millennium. If this is recalculated using calibrated ages, then the curve in this period is still steeper, as has been calculated by Mörner (1976, fig. 1). When speed of sedimentation is to be calculated, calibrated ages must be used (Petersen 1981).

Sea Level Changes in the Atlantic and Subboreal

The question of later changes in sea level has particularly interested Danish researchers. One can point to the date 1937 as the start of these investigations (Iversen 1937; Jessen 1937; Troels-Smith 1937, 1939, 1942; Iversen 1943).

In general these studies, especially through the work by Iversen, succeeded in showing 4 Littorina transgressions: the Early Atlantic, the High Atlantic, the Late Atlantic and the Early Subboreal.

These are depicted by Jacobsen (1982) in his preliminary study of the Littorina transgressions in Trundholm Mose in northwest Sjælland.

For the Vedbæk area in northeast Sjælland, Christensen (1982) has shown sea level changes covering 3000 years from 7500 BP, i.e. including the Early Atlantic

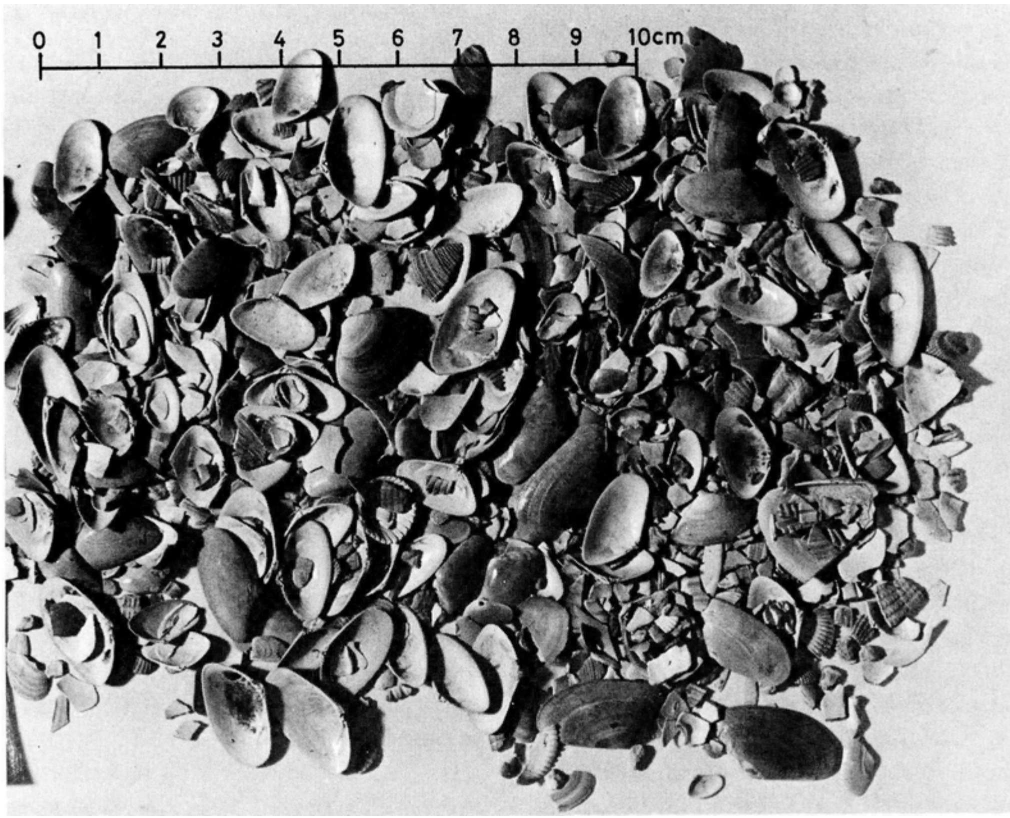

Fig. 8. C-14 dated shells from 1910±100 before 1950 (BP). The wedge shaped *Donax vittatus* predominates. The sample is taken from 6 km south of the present coast of Vester Hanherred, from the ±0 m contour. As *Donax vittatus* has never occurred *in* the Limfiord, the find demonstrates that this part of the country was built up from the Skagerrak side. The area is palaeogeographically called the Donax Sea after this mussel.

transgression. It is, however, stated by Christensen (op. cit. p. 101) that the reason for the presence of 3000 years record of sea level changes is due to Vedbæk's location in an area of favourable conditions between the isostatic uplift of the land and the eustatic rise of the sea.

One must, however, stress that the drawing of sea level curves covering the 3000 years from the Early Atlantic also requires very detailed methods, because one is measuring changes of as little as 0.5 m.

It would not be possible to establish the depth tolerances of marine invertebrates (particularly molluscs) used as shoreline indicators (Petersen in press) to within such narrow limits. Their depth interval can rarely be given more precisely than to the nearest 2 m, which is the amplitude one operates with for eustatically determined changes (Blake 1975) in the Holocene after the Early Atlantic transgression.

Of the above-mentioned investigations of the Littorina transgressions, those of Troels-Smith at Amager (1939) and Dyrholm (1942) are also related to coastal settlements. Iversen's studies (1937, 1943) were based on diatoms, pollen and Hystrix in fiords, where height of the threshold is crucial for the transgressional history.

Korup Lake on the Djursland peninsula was one of the fiords Iversen investigated. The whole series of layers is marine, and according to Iversen only the quantity of Hystrix indicated the transgression. These Hystrix (Hystrichosphaerids) are the remains of organisms many of which also live in Danish waters today. It was Iversen's belief, as Christensen (1982) writes, that these Hystrix were washed out of late glacial deposits during periods of transgression. As they are found in Danish waters today, however, one must go further, and to follow up Iversen's idea it is necessary to establish which of these organisms derive from the late glacial deposits.

Recent investigations at Korup Lake by Harald Krog (pers. comm.) have also shown that the Hystrichosphaerid curve is more complex than Iversen's investigations suggested.

What is at stake here is the maximum connection with open water, and thus higher salt content in the water. Maximum values of the molluscan fauna could therefore also be used. In this connection *Ostrea edulis* appears in Korup Lake around the High and Late Atlantic transgressions in a rich faunal association, which is contemporary with the date for the site of Barkær next to Korup Lake in the Late Atlantic (Troels-Smith 1982).

In the faunal succession off the Dyrholm settlement on Djursland there is also a level with *Ostrea edulis* and *Tapes aureus* (a few finds) dated to the High Atlantic.

It ought therefore to be possible to establish some of the above mentioned transgression maxima by purely faunal means.

This leads on to the question of when the highest marine limit was reached in various parts of the country. A distinction must be made here between those parts of the country with raised marine areas (Mertz 1924), and those where there was a continuing transgression until the Iron Age, i.e. the areas northeast and southwest respectively of Forchhammer's line from Nissum Fiord to the north tip of the island of Falster.

From the various studies of the Littorina Sea it transpires that the highest sea level in Vendsyssel (Dybvad) was reached in the High Atlantic. At Brovst in north Jutland (Andersen 1970) and at Vedbæk in northeast Sjælland it was reached in the Late Atlantic. In Himmerland (at Ertebølle), Djursland (at Dyrholm) and Amager it was reached in the Subboreal, and in southwest Sjælland (Præstø) (Mikkelsen 1949) in the Subatlantic.

This shows the tendency, already noted by Iversen (1943) for areas towards the periphery of the zone of land uplift to have their highest marine levels at later times.

In the downwarping area, investigations of submarine settlements show that the High Atlantic transgression in the Danish area cut shorelines which are now at –3 m. This fall of 3 m took place over 4000 years, up to the Iron Age, when the lowering of the land must have ceased because settlements of this epoch are still located as they are thought to have been when they were established (Petersen 1985 b).

It has not been possible to demonstrate the existence of the eustatic fluctuations, which must also have been in operation in the downwarping zone, through faunal investigations in the Danish area.

The Holocene Marine molluscan Fauna

The faunal association in the earliest Holocene marine deposits in Denmark is known from borings in northern Jutland, particularly the Limfiord, where deeply eroded valley systems formed during the continental period are also the places which were flooded by the Boreal and Early Atlantic transgressions (Petersen 1981, 1985 a).

It emerges from this that in the period 7860 – 7380 BP, in the depth interval 24.0 – 25.0 m below present sea level, virtually all the marine species that can be said to characterize the marine fauna of the Danish region were present (cf Petersen 1981, fig. 4). Littoral elements are found: *Ostrea edulis*, *Mytilus edulis*, *Tapes* (3 spp), *Tellina* (2 spp), *Gibbula* (2 spp), *Littorina* (3 spp) and *Retusa* (2 spp), as are deeper water forms: *Nucula* (3 spp), *Montacuta* (2 spp), *Cardium echinatum*, *Cardium exiguum*, *Cyprina islandica*, *Venus* (2 spp), *Abra* (3 spp), *Cultellus pellucidus*, *Spisula subtruncata*, *Hiatella arctica*, *Corbula gibba*, *Thracia papyracea*, *Lacuna* (3 spp), *Rissoa* (5 spp), *Natica intermedia*, *Nassa pygmaea*, and *Cylichna* (2 spp).

The fauna in these early transgression layers, even in the innermost parts of the fiord systems, are prolific in the whole country. It is thus remarkable to find the genera *Ostrea* and *Tapes* represented in both the southern Fyn region and the Little Belt area during the Atlantic. *Ostrea edulis* is known both as juveniles in intact gyttja samples from Møllegabet off Ærø, and as fully grown in the shell middens around Tybrind Vig (Petersen 1985 b).

This is a parallel situation to the Eemian, when these genera are also present. The latest, rather rare finds of *Ostrea edulis* and *Tapes aureus* within the Baltic date from as recently as the Iron Age, as shown by studies of Iron Age coastal settlements (Poulsen 1978; Petersen 1980).

The extinction of the *Tapes* species, apart from *T. pullastra*, in Denmark in relatively recent times has meant that they are regarded as type fossils for the Stone Age sea, which is also called the Tapes Sea, in northern parts of Denmark. *Tapes aureus* is regarded as belonging to the younger *Tapes* deposits (Nordmann 1910). It should be noted, however, that as mentioned above *Tapes aureus* is found in deposits of Iron Age date in southern Denmark, and in the Limfiord until about 2000 BP (Petersen 1976).

Regarding later immigrants, it is not correct that *Mya arenaria* characterizes deposits of older than late historic date, because the latest investigations have shown that this mussel only arrived in Europe in the post-Columbian era (Petersen 1976). The common term "Mya Sea" for the most recent subfossil marine deposits must therefore be given up.

The mussel *Donax vittatus* can on the other hand be mentioned as a late immigrant characterizing our earlier Subatlantic deposits. It is today common on the sandy western coasts, but is found in subfossil deposits in northwestern Jutland dated to 2110 BP (Petersen 1985 a) in the region near Agger, and is a type fossil for the latest marine deposits laid down in the Vester Hanherred area of northern Jutland by the Donax Sea (Petersen 1976) (fig. 8). Its late arrival at our coasts is supported by investigations on the Swedish west coast (Hägg 1913). It may be mentioned that *Donax vittatus* is known from Eemian deposits in southwestern Denmark, but is not found in the Baltic Eemian deposits (Nordmann 1928).

As mentioned above, the western Baltic in earlier times contained species that were characteristic of the Eemian in the same region; but it must be presumed that, in common with the rest of Denmark, species diversity is declining. The present Limfiord fauna thus consists of 85 shell-bearing molluscs, while we know of 138 from the subfossil deposits. This could be evidence that the maximum of the present *interglacial* has passed. Regarding individual late immigrants, special biotopic conditions and access routes may be relevant. The recent appearance of *Astarte borealis* in the Baltic fauna is an example of access routes. The species is regarded as a relict from the glacial period in this area, and as mentioned above the palaeo-Kattegat has existed virtually without a break for the last 100,000 years. As the palaeogeographic map of the late Weichselian shows, an arm of the arctic-boreal sea stretched right down to the southernmost part of the Kattegat at this time. This is the only possible way in which species like *Astarte borealis* could have got into the Baltic at the time of the early Littorina Sea.

The Regional Holocene Transgression History

This attempt to give a regional review of the Holocene transgression history is inspired by the many dates which have, during the past few years, made it possible to pinpoint shorelines in time. It also includes an evaluation of the depth indication and shoreline indication given by the molluscs used for the datings. A body of material has therefore been selected from the literature and from my own investigations which is thought most likely to refer to shoreline formation. This material does not therefore create curves of the sort produced by Charlie Christensen (1982), covering 3000 years at Vedbæk. The intention is solely to present the major changes in sea level.

By the major changes in sea level are meant the Early Atlantic transgression, the establishment of the maximum marine transgression, and the fixing of the point in time when the curves approach present day values.

It would of course be nice if the body of data was larger, but it does at least spread fairly evenly throughout Denmark. The data is therefore plotted from a little south of 55°N up to 58°N, in a three dimensional graph where the other two axes are time and sea level (fig. 9).

In plotting the data from individual sites their longitude must be born in mind as a fourth dimension. In all, 58 observations have been included in the figure.

As mentioned above, the development of the maximum transgression level in Denmark is metachronous, and it has only been established at a few sites so far. Cutting the shoreline displacement curve at, for example, the plane defined by present sea level should, I presume, show this situation. Variations in level caused by (for example) neotectonic movements should also be relevant beside the isostasy (fig. 10).

The latter condition is regarded as the reason for the very great age (8500 BP) of the Tværsted region of northern Vendsyssel, which is an extrapolation from the dated shells at the +6 m contour at 8250 BP (Krog 1984). If one examines the data from further south, Store Vildmose, Aggersund, Torsholm (Viborg), Korup Lake and Vedbæk, the values here are 1000 years younger, between 7200 and 6700 BP.

With longitude in mind, the observations can be fitted into the pattern (see fig. 12) that the isobases present of the uplifting of Denmark northeast of the

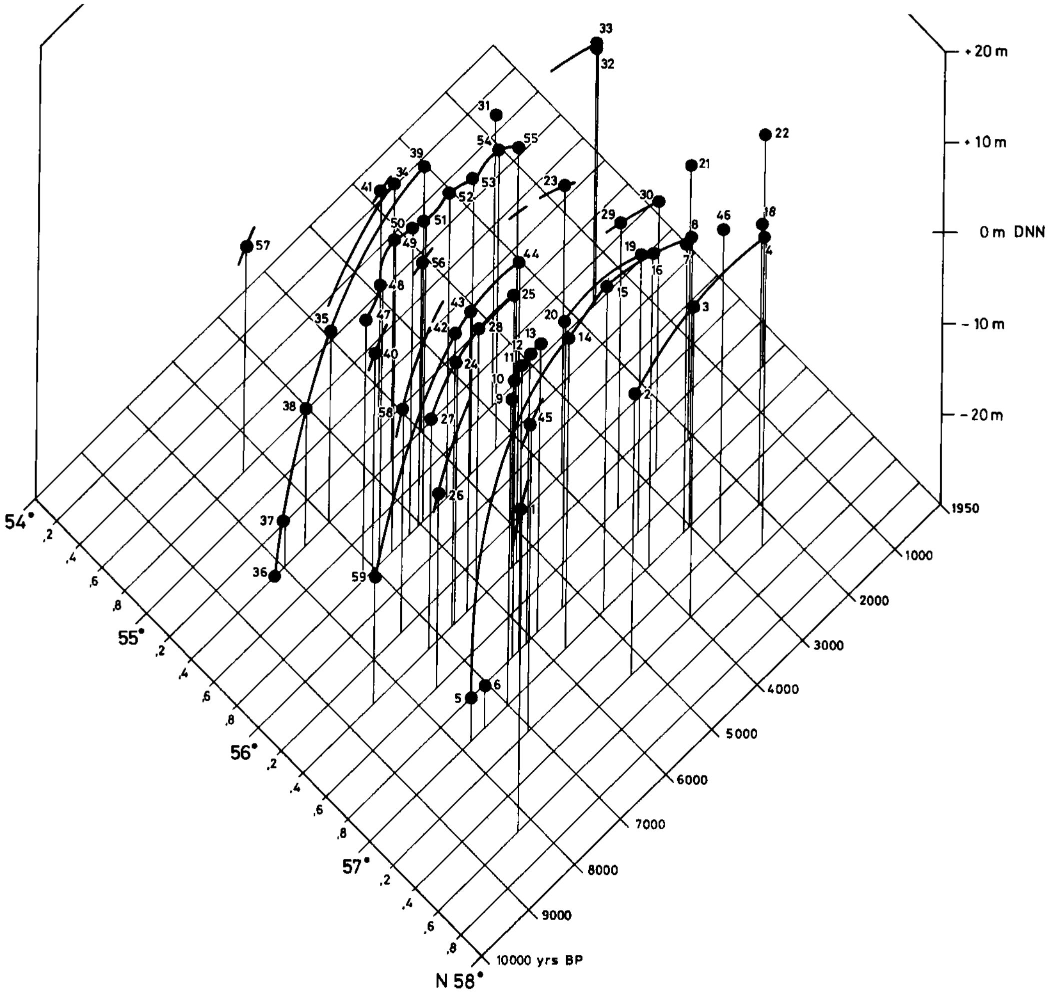

Fig. 9. The three dimensional graph plotting latitude, time and sea level, with the observations listed below (Table 1). Observations with the same longitude are connected.

Forchhammer line. They also offer support to the suggestion put forward by Iversen that the attainment of the marine maximum should take place later in areas peripheral to the uplift zone. Thus the present level of about 0 m was reached on Samsø at 6500 BP, and at Pinemølle on the Great Belt at 5000 BP.

The approach of the shoreline displacement curve to present levels is also shown (fig. 10), and although this is only a suggestion it does show a tendency to flatten out earlier in the south. Horsens Fiord is an exception to this, however, as the Iron Age shell middens there are the first settlements to lie on the present coast.

Against the above observations for the area north of the uplift line, the dated coastal settlements from the area to the south clearly fall into an area of downwarping, lying below the recent sea level (fig. 9). The model put forward above also involves holding time constant and then cutting through the shoreline displacement curves; this permits an understanding of the land-sea configuration at the chosen point in time.

It can only be my sincere hope that more data will become available for sea level changes for inclusion in the model. The remarkable rise in sea level in the Boreal and Atlantic periods shows clearly in the three dimensional computer plot viewing Denmark from the northeast at an angle of 30°, where the time transgressive movement over Denmark (as a linear function) appears as the third dimension (fig. 11).

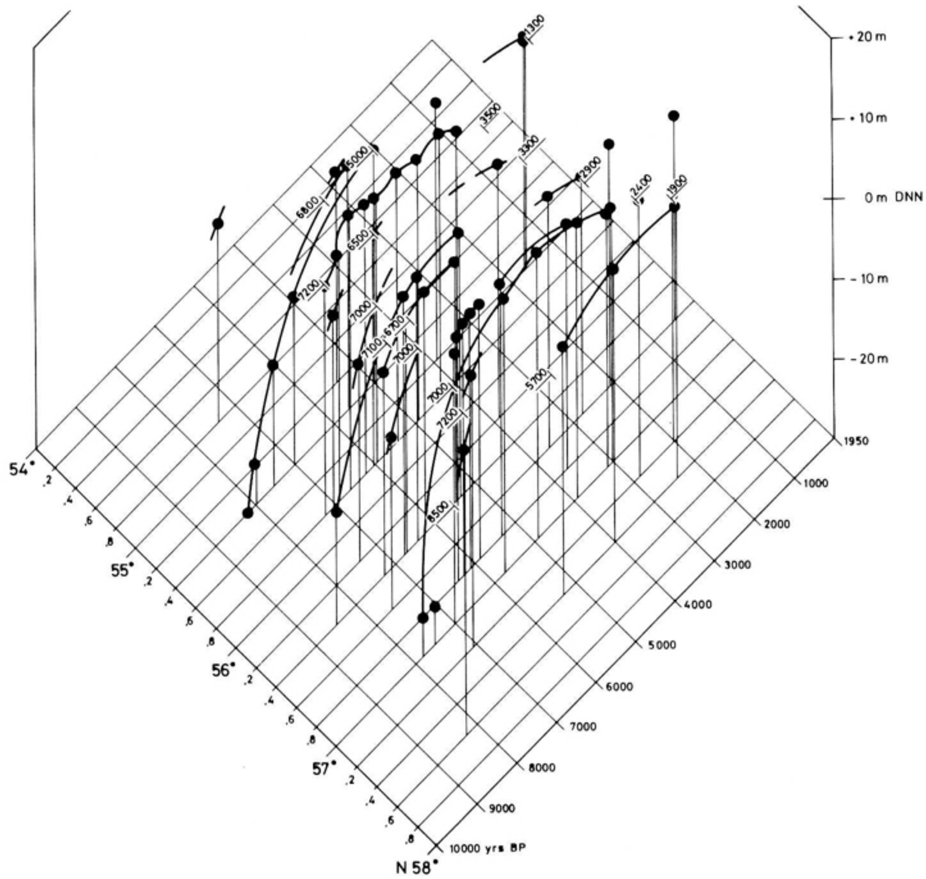

Fig. 10. A plane is inserted at the ±0 level, and the points where it cuts through the curves marked with the time before 1950 (BP).

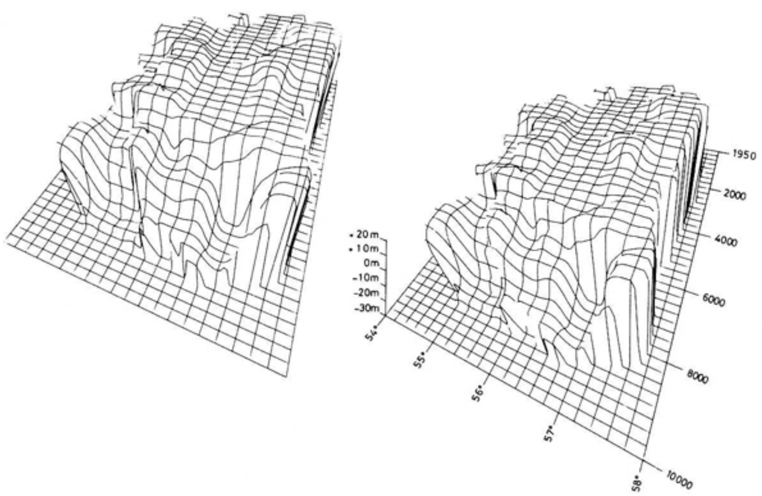

Fig. 11. Computer plot of the same number of observations as in fig. 9, using the same co-ordinates. Some evening out has occurred, as the squares are divided into 100 × 100 grids, each being given a value extrapolated from the four nearest observations. The sea level change in the early Holocene is clearly visible. This crosses the Danish area, which is plotted as a linear function from north to south.

No.	Latitude	BP	Elevation	Locality	Material	Lab. No.
1	57.6	8250	+6.0	Tværsted	*Cardium edule*	K-1472
2	57.4	5240	+1.3	Frederikshavn	*Ostrea edulis/Dosinia exolata*	K-1237
3	57.4	3980	+4.0	Frederikshavn	*Ostrea edulis/Dosinia exolata*	K-1236
4	57.4	2440	+4.0	Frederikshavn	*Cardium edule*	K-1246
5	57.0	7860	−25.0	Vust	*Cirripedia*	K-3281
6	57.0	7660	−25.0	Vust	*Mytilus edulis*	K-3280
7	57.0	3250	+0.8	Vust	*Tilia* sp.	K-2747
8	57.0	3130	+1.7	Vust	*Tapes aureus*	K-3221
9	57.0	6980	+3.5	Gjøttrup	*Ostrea edulis/Cardium edule*	K-2480
10	56.8	6650	+0.5	Skrandrup	*Cardium edule*	K-2383
11	56.8	6420	+1.0	Livø	*Cardium edule/Scrobicularia plana*	K-2477
12	56.8	6260	+1.5	Skrandrup	*Cardium edule*	K-2475
13	56.8	5910	+1.5	Livø	*Cardium edule*	K-2478
14	57.0	5790	+3.0	Ullerup	*Cardium edule*	K-2570
15	57.0	4990	+6.0	Aggersund	*Ostrea edulis*	K-2481
16	57.0	3990	+4.0	Bjerregd.	*Ostrea edulis*	K-2479
18	57.2	1910	+0.0	Kovad Bro	*Donax vittatus*	K-2384
19	56.8	3690	+0.5	Ertebølle	*Cardium edule*	K-3679
20	56.8	5280	+1.5	Ertebølle	*Cardium edule*	K-3680
21	56.6	2110	(+0.0)	Agger	*Cardium echinatum*	K-4254
22	56.6	410	−4.0	Agger	*Cardium edule/Macoma balthica*	K-4186
23	56.2	3860	+0.7	Korup Sø	*Cardium edule*	K-3681
24	56.4	6550	−1.5	Fiskbæk	*Mytilus edulis*	K-3547
25	56.4	5400	−0.5	Fiskbæk	*Cardium edule*	K-3548
26	56.6	7620	−8.5	Torsholm Sø	*Ostrea/Mytilus/Thracia/Corbula*	K-3431
27	56.4	7150	−5.0	Jordbro Å	*Ostrea edulis*	K-3432
28	56.4	6190	+1.0	Romlund	*Ostrea edulis*	K-3433
29	56.6	3650	+1.5	Torsholm Sø	*Ostrea edulis*	K-3283
30	56.6	2750	+0.5	Torsholm Sø N.	*Cardium edule/Venerupis aurea*	K-3157
31	55.6	3890	+3.6	Vær (Horsens)	(*Mytilus edulis*) Sb3.	K-3158
32	55.6	1520	+0.2	Vær (Horsens)	(*Mytilus edulis/Venerupis aurea*) S.B.	K-3159
33	55.6	1480	+0.5	Vær (Horsens)	(*Mytilus edulis/Venerupis aurea*) S.C.	K-3160
34	55.4	5610	+1.0	Trylleskov (Køge)	*Halichoerus grypus*	K-3075
35	55.4	7170	−9.5	Pinemølle	*Cardium edule/Macoma balthica*	K-2382
36	55.4	(8200)	−30.0	Pinemølle	interpolated	Petersen 1978
37	55.4	(8000)	−25.0	Pinemølle	interpolated	Petersen 1978
38	55.4	(7500)	−15.0	Pinemølle	interpolated	Petersen 1978
39	55.4	(5000)	−2.0	Pinemølle	interpolated	Petersen 1978
40	55.8	7030	−5.7	Trundholm	Mollusca	Jacobsen 1983
41	55.2	5320	−2.9	Tybrind Vig	Wood	Andersen 1983
42	56.4	6780	+1.8	Dyrholm	*Cardium edule*	K-4092
43	56.4	6510	ca. +2.5	Dyrholm	*Ostrea edulis*	K-4094
44	56.4	5350	ca. +3.0	Dyrholm	*Cardium edule*	K-4096
45	57.2	7100	+4.3	Store Vildmose	Peat	K-3313 and K-3312
46	57.2	2930	+4.5	Læsø	*Physeter catodon*	Hansen 1980
47	55.8	7250	+0.0	Vedbæk	interpolated	Christensen 1982
48	55.8	6950	+1.5	Vedbæk	interpolated	Christensen 1982
49	55.8	6450	+3.0	Vedbæk	interpolated	Christensen 1982
50	55.8	6200	+4.0	Vedbæk	interpolated	Christensen 1982
51	55.8	5950	+3.5	Vedbæk	interpolated	Christensen 1982
52	55.8	5450	+5.0	Vedbæk	interpolated	Christensen 1982
53	55.8	4950	+3.8	Vedbæk	interpolated	Christensen 1982
54	55.8	4450	+4.5	Vedbæk	interpolated	Christensen 1982
55	55.8	3950	+3.0	Vedbæk	interpolated	Christensen 1982
56	55.8	6030	−0.9	Stavns Fjord (Samsø)	Wood	K-3996
57	54.8	ca. 7450	ca. −5.0	Argus	Archaeological	Fischer (pers.comm.)
58	56.2	7370	−9.0	Korup Sø	*Cardium edule*	K-3989
59	56.4	ca. 8500	−16.0	Grenå	Pollen dating	Krog 1979

Table 1.

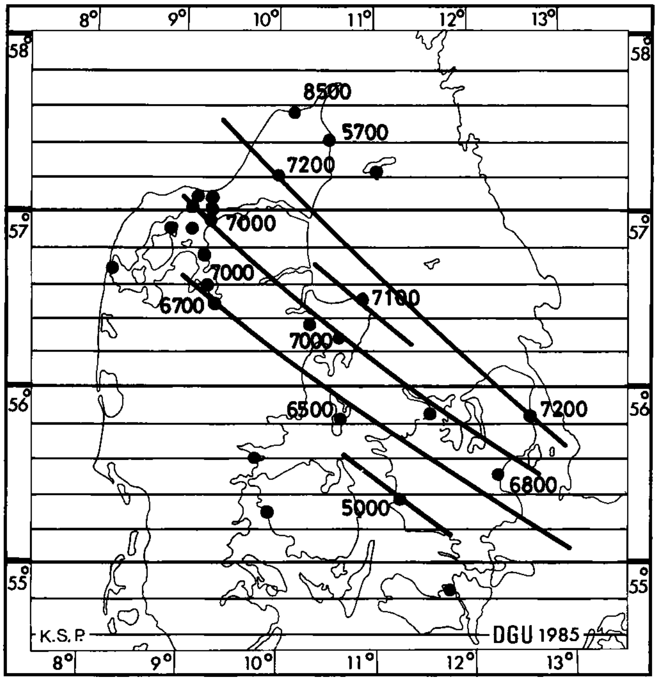

Fig. 12: Map showing the sites and times that the sea level displacement curves in fig. 9 intersect with the ±0 m level. Isolines are drawn between them. These isolines agree with the progression known from the isobases. Note a diverging value between Tværsted and Frederikshavn.

CONCLUSION

The foregoing presents the main features of an attempt to establish the chronology of shoreline development in Denmark. If the Holocene situation is compared with palaeogeographic development in the earlier part of the Late Pleistocene (put forward in the first part of this work), then it can be seen that, despite the changes caused by the Weichselian glaciations, a land-sea configuration has become established in our own time which is in many ways similar to that of the Eemian – also regarding the sea level.

Minor differences in southwestern Denmark regarding level may have been caused by the greater glaciation preceding the Eemian, when the whole of Denmark was covered with ice; the limits of the area of isostatic uplift in the Holocene, however, is in close agreement with the area of the Weichselian glaciation.

In presenting the late Quaternary as a whole, one aim has been to point out that parts of the Danish landscape lay outside the glaciated area right back to the Eemian, and that the Weichselian glaciations have either been partial, as for the Early Weichselian, or of short duration, as for the Late Middle Weichselian advance which covered the greatest part of Denmark. Thus the present Kattegat region has been a factor in land-sea configurations for the last 120,000 years, interrupted only by the glaciation from about 22,000 to 15,000 BP.

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