Late Pliocene Greenland – The Kap København Formation in North Greenland

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The Kap København Formation, North Greenland, is a 100-m thick succession of predominantly shallow marine nearshore sediments, dated to c. 2.4 ma. The abundant well preserved remains of mosses, land plants, foraminifers, ostracodes, insects, cladocers, molluscs, and a few vertebrates enable a detailed reconstruction of terrestrial and marine environments and climate. The sediments indicate a complex sea-level history implying combined glacioisostatic and -eustatic control. This is supported by the faunal and floral development from arctic to subarctic and boreal conditions, and the record probably reflects the demise of the first major Cenozoic ice sheet, the Praetiglian, over the area, and the onset of the succeeding Tiglian A interglacial. The record ends with the attainment of the interglacial sea-level highstand and climate optimum when forest tundra reached the world's northernmost coasts. It is inferred that the duration of sedimentation was a half obliquity cycle, i.e. 20,000 yr, at the most.

Keywords: Pliocene, Praetiglian, Tiglian, palaeoenvironments, sea-level change, Greenland

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Since its discovery in 1979 the Upper Pliocene Kap København Formation at 82°30′ N in Peary Land, North Greenland (Fig. 1), has yielded an insight into the early Arctic environment that is unparrelled in its richness of detail. The present paper gives an overview of the results. We suggest, based on the sedimentary succession, climate development, and dating evidence that the sedimentation was controlled by glacioisostasy/eustasy and reflects the melting of the Praetiglian ice sheets and the beginning of the succeeding Tiglian A interglacial, i.e. the duration of the record is no longer than 20,000 years.

Appendix 1 lists remains of terrestrial and marine organisms found in the sediments. Appendix 2 presents new analyses of $^{87}Sr/^{86}Sr$ in mollusc shells, giving evidence of local hydrology.

Historical

Sighted from afar and named in 1907 by a sledge party during the Danmark Expedition, the area around Kap København has a research record that is surprisingly rich for one of the world's most inaccessible areas. The first scientist to visit the area was Lauge Koch, who during his sledge-journey around Greenland's northern tip in 1921, on a bright day spent several hours triangulating and making observations from the top of one of the highest of the hills that characterise the area. A result of this was a sketch showing the hills as terminal moraines, which he believed to represent the ultimate northern extension of the Inland Ice – i.e. the ice sheet never reached the northern tip of Greenland. This sketch was published repeatedly over the next ten years, and the ideas agreed on by later visitors, who were equally impressed by the sizeable hills (Koch 1925, Troelsen 1952, Davies 1963). As a consequence, until recently standard textbook maps
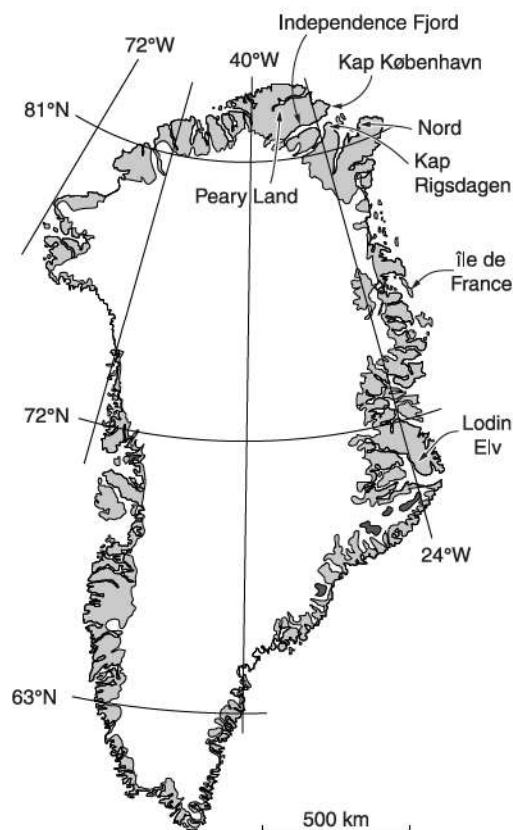
Fig. 1. Location of localities mentioned in the text

of maximum worldwide glaciation have often showed the northern tip of Greenland jutting out from under the ice cover. Koch also noted the driftwood found among the hills.

When GGU (Geological Survey of Greenland, now part of GEUS) initiated its major geological mapping project in North Greenland, the Kap København area was scheduled as one of many 2-persons/5-days camps, and visited in late July 1979. It soon appeared that the large hills were not moraines but erosional remnants of a once thick and continuous cover of non-glacigene aquatic sediments over the coastal plain at the northeast corner of Independence Fjord and the Greenland Sea. Since only a thin bed of till capped them, the aquatic sediments were considered to be last interglacial (Funder & Hjort 1980, Fredskild & Røen 1982).

The area was visited again in 1980, but the major investigation was in 1983 when six scientists stayed for one month in the area. One of the most spectacular finds came shortly before the end of the field season when cones, needles, and twigs of conifers were found in a lens of organic detritus, showing that the wood came from indigenous trees. Shortly afterwards, Feyling-Hanssen using foraminifer faunas was able

to show that the previous age estimate was much too young, and the age was within the "Plio-Pleistocene" (c. 1.7-2.5 ma, Funder et al. 1985, Feyling-Hanssen 1990). Follow-up field work in 1986 concentrated on the sites with tree remains, and this was our last visit to the area (Bennike & Böcher 1990). Since then, painstaking work by many experts concentrated on analyses of the fossil content of the collected samples. This has resulted in a large number of papers centred on a series of monographs on foraminifers (Feyling-Hanssen 1990), vascular plants (Bennike 1990), ostracodes (Brouwers et al. 1991, Penney 1993), insects (Böcher 1995), and marine molluscs (Símonarson et al. 1998).

The sedimentary succession, sea-level-change

The Kap København Formation is a ca. 100-m thick succession of sand and clay, locally with abundant organic detritus. The sediments cover the coastal plain along a 30–40 km stretch of coastline, extending up to 10 km inland (Fig. 2). They rest conformably on till, observed at two localities (localities 7 and 39, Fig. 2), and are also overlain by till, although this is thin and discontinuous. To the north The Kap København Formation is separated from the mountain area of Kim Fjelde by a younger flood plain along the Ladegårds-å stream. The south western outcrop boundary is also erosional, eroded by a later glacier in Independence Fjord, while the extension to the east is uncertain owing to poor exposure. The glacier advance that laid down the covering till was probably also responsible for the large scale folding and thrusting of the sediments. The stratigraphy is further obscured by large scale synsedimentary slumping, especially in the organic-rich units B1 and B3 (Funder et al. 1984).

Within the area of the Kap København Formation more than 150 exposures, ranging from 1 to c. 100 m in thickness, have been studied and numbered, and these numbers have been used in all post-1983 publications (Fig. 2). The thickest and lithologically most varied succession is the type section (locality 50, Fig. 2). This was the first exposure to be discovered, and it has since been used as a master for the sedimentation history in the whole area (Fig. 3). The numerous other sites have been correlated to this by lithology (Bennike 1990, Símonarson et al. 1998), based on the assumption that the sedimentary successions all represent the same history of sea-level change (Fig. 3). However, the dislocation of the sediments makes correlation within the area difficult, and several models could fit the observations. The model presented here
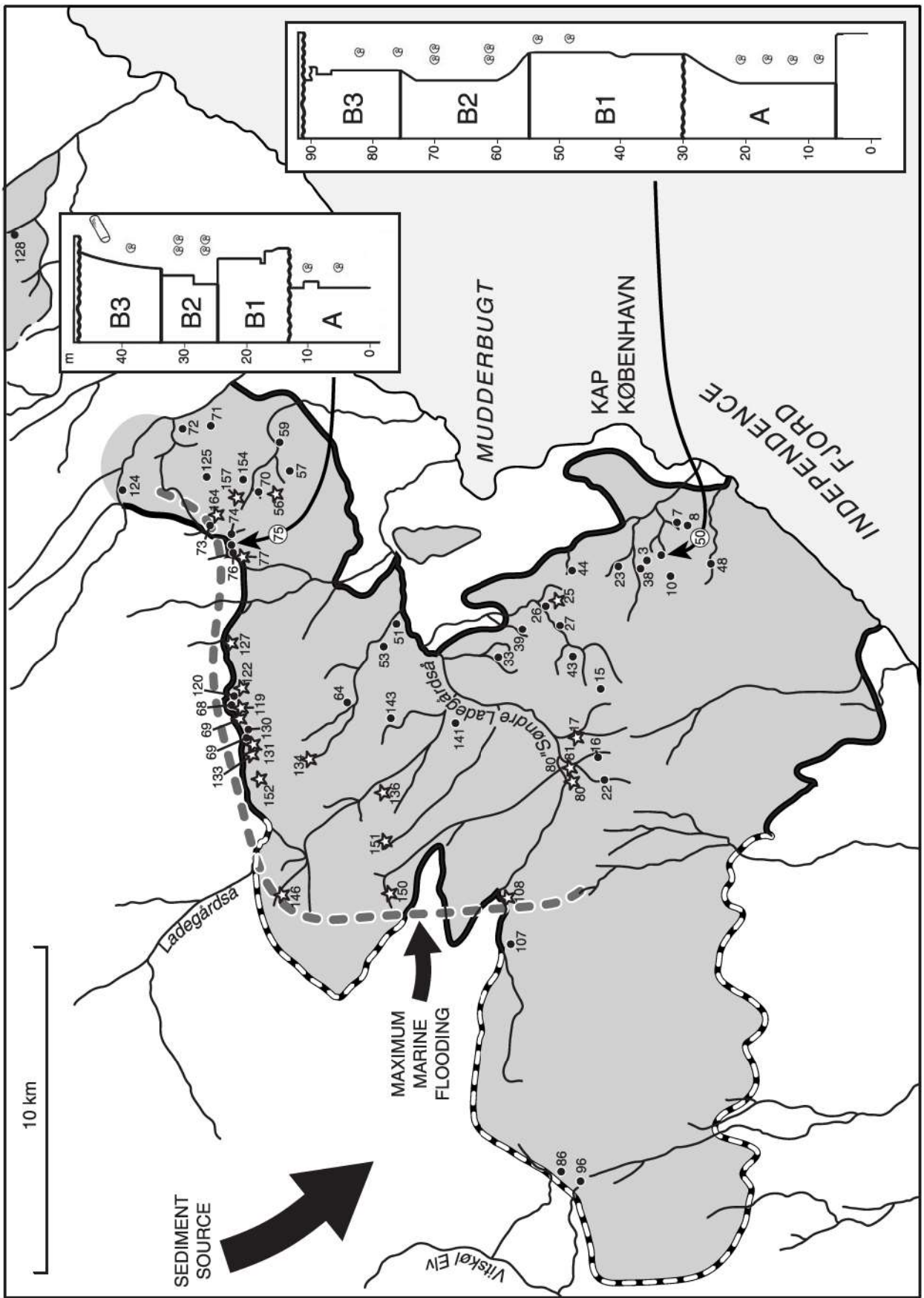
Fig. 2. Distribution of the the Kap København Formation (shaded), and lithology and thickness of an inner and an outer coast sediment succession (localities 75 and 50). Numbered localities have been mentioned in previous publications (Feyling-Hanssen 1990, Bennike 1990, Böcher 1995, Simonarson et al. 1998). Asterisks mark occurrence of driftwood (from Bennike 1990).

aims at combining sedimentological, biological and dating evidence (Fig. 3).

The succession is divided into two members, the predominantly clayey member A and the predominantly sandy member B, which at all localities are separated by an erosional boundary (Fig. 3). Member A is bounded at its base by a deglacial flooding surface (immediate attainment of highstand by the collapse of a marine-based glacier), followed by up to 50 m thick laminated mud. At locality 50 the laminated mud is coarsening upwards into horizontally laminated sand (Símonarson et al. 1998). This succession is similar to Holocene marine successions found in all parts of Greenland and is interpreted to be glaciomarine, formed during isostatic rebound.

The overlying 40–50 m thick member B is dominated by horizontally laminated sand, but a fine grained interval in the middle at most sites allows distinction between three units, B1, B2, and B3. The lowest unit, B1, begins with truncated sets of low angle cross stratified sand, interpreted as foreshore facies (Figs 19 and 20 in Bennike 1990), this is overlain by a fining upwards succession of horizontally laminated sand indicating increasing water depth. This trend continues into the fine grained unit B2, which is dominated by silt. This unit attains its maximum thickness, 20 m, in the coastal area. Here it is composed of massive heavily bioturbated mud, while further inland the thickness is only 2 m, and the sediments are fine laminated silt and fine sand (Fig. 2). With a gradational transition unit B2 is again overlain by the coarsening upwards horizontally laminated sand of unit B3. This unit contains abundant organic debris, notably layers of mosses and laminae of leaves and small twigs as well as wood. At most sites unit B3 has a thickness of c. 15 m, but the thickness may amount to 40 m.

From its lithological development member B is interpreted to reflect a period of sea-level rise beginning with transgression of the area at the base of unit B1 (Fig. 3). For most of the time sea-level rise and sedimentation kept pace, but for some time, marked by unit B2, the sea-level rise overtook the sediment supply and maximum water depth was attained. At locality 50 where all units are preserved the thickness of the marine sediments, c. 40 m, gives a minimum for the magnitude of relative sea-level rise. At the top of unit B3 the marine sediments are erosionally overlain by sand devoid of marine fossils, interpreted here as deltaic and indicating regression and incision.
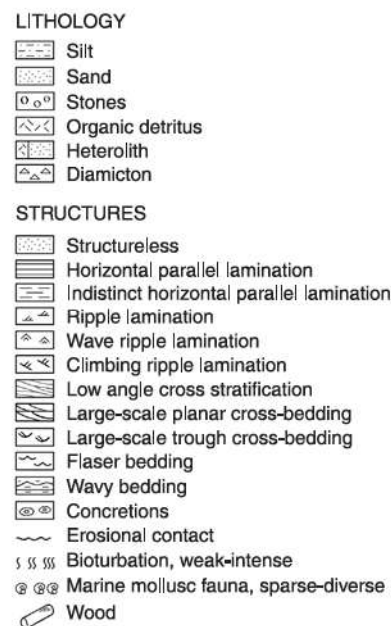
In areas within a radius of 10–15 km from Kap København sedimentary facies and fossil content in the exposures are sufficiently similar to allow reasonably certain correlation (Bennike 1990), even though the landwards decrease in thickness of unit B2 makes the differentiation between units B1 and B3 difficult (Fig. 2). Maximum flooding is probably marked by the most landward appearance of driftwood in unit B3, which forms a line parallel to and 10–15 km inland from the present coast of Mudderbugt (Fig. 2).
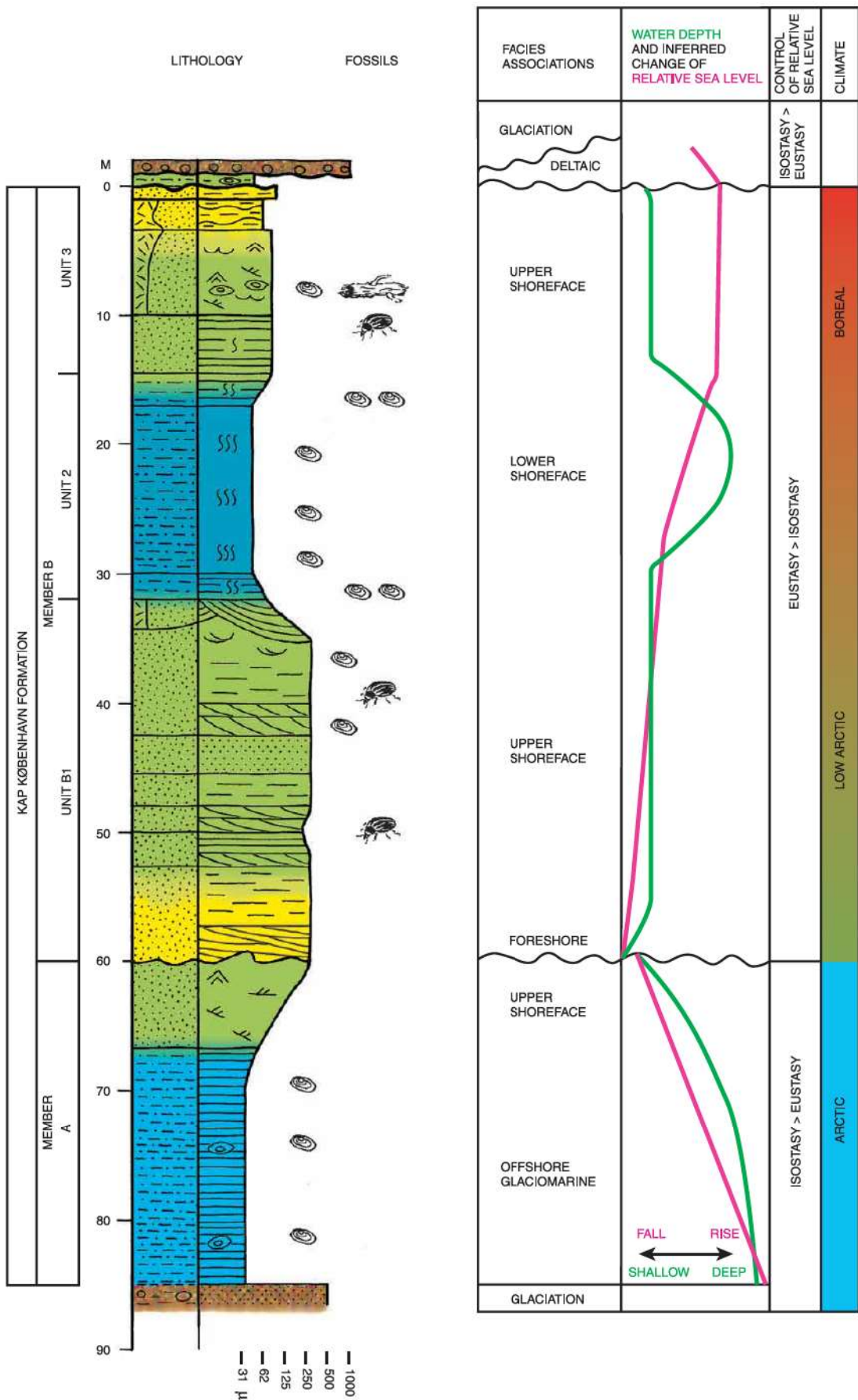
Further away the facies change more and correlation is less certain. In the western part, the sediments are fluvial and devoid of primary fossils and heavily tectonised by overriding of a later glacier. The correlation with these sediments is based on the "allochthonous fauna" found at the base of the fluvial succession (see below), and the base of the fluvial sediments in the eastern part of the area (localities 96, 98) is correlated with members A and B, implying that the sediment source for the Kap København Formation was in the west, probably a predecessor of the present rivers Vitskøl Elv and Ladegårdså, which now drain a large area in inner Peary Land (Fig. 2).

On the eastern margin isolated localities (72 and 128) yield marine faunas with amino acid ratios similar to those from the central area, but with both marked faunal and floral similarities and dissimilarities to the central area. Different correlation schemes have been proposed for these occurrences (Feyling-Hanssen 1990, Brouwers et al. 1991). Using lithological criteria, we suggest that the sediments at loc. 72 belong to unit B2 and those at locality 128 to B3, and the faunal differences are due to variation in the local environments. An exposed section at Kap Rigsdagen

Fig. 3. Sedimentology and environmental development of the Kap København Formation. The composite section is based mainly on locality 50, but includes also evidence from other localities.

LITHOLOGY

- Silt
- Sand
- Stones
- Organic detritus
- Heterolith
- Diamicton

STRUCTURES

- Structureless
- Horizontal parallel lamination
- Indistinct horizontal parallel lamination
- Ripple lamination
- Wave ripple lamination
- Climbing ripple lamination
- Low angle cross stratification
- Large-scale planar cross-bedding
- Large-scale trough cross-bedding
- Flaser bedding
- Wavy bedding
- Concretions
- Erosional contact
- Bioturbation, weak-intense
- Marine mollusc fauna, sparse-diverse
- Wood

LITHOLOGY   FOSSILS

| FACIES ASSOCIATIONS | WATER DEPTH AND INFERRED CHANGE OF RELATIVE SEA LEVEL | CONTROL OF RELATIVE SEA LEVEL | CLIMATE |

KAP KØBENHAVN FORMATION

MEMBER B

MEMBER A

UNIT 3

UNIT 2

UNIT B1

GLACIATION

DELTAIC

UPPER SHOREFACE

LOWER SHOREFACE

UPPER SHOREFACE

FORESHORE

UPPER SHOREFACE

OFFSHORE GLACIOMARINE

GLACIATION

ISOSTASY > EUSTASY

EUSTASY > ISOSTASY

ISOSTASY > EUSTASY

BOREAL

LOW ARCTIC

ARCTIC

FALL   RISE

SHALLOW   DEEP

31 µ 62 125 250 500 1000

on the other side of Independence Fjord (Fig. 1), also has amino acid ratios and some faunal and floral peculiarities similar to the Kap København Formation (Bennike 1989, Símonarson et al. 1998), and is correlated with it.

The sea-level history suggested here therefore comprises first a period of relative sea-level fall represented by member A (Fig. 3). This was followed by renewed sea-level rise and transgression, which again ended with sea-level fall (units B1, B2, B3). The inference is that the sedimentation began when an ice sheet over the area disintegrated and isostatic rebound caused a fall in relative sea level. Later, when the climate had changed to low arctic, eustatic sea level rise caused renewed transgression and while the climatic warming continued sea level rose until the melting of ice sheets on land came to an end and the interglacial highstand was achieved. At this time isostatic emergence again became dominant and the nearshore sedimentation changed to sediment bypass (Fig. 3). This pattern of sea-level change is characteristic for formerly glaciated areas where local deglaciation and isostatic emergence leads global eustatic sea-level rise (Boulton 1990, Lambeck & Chappell 2001), and is well known from ice-sheet marginal areas after the last ice age. A similar sequence of events has been proposed for the last interglacial in central East Greenland (Funder et al. 1998). An implication of this model is that the duration for the sedimentation of the Kap København Formation was much shorter than previously assumed, as discussed below.

Age

Símonarson et al. (1998) suggested that the Kap København Formation was deposited within the interval isotope stage 100–91, between 2.52 and 2.35 ma in the orbitally-tuned oxygen isotope record (Shackleton et al. 1995), and correlated with the Praetiglian-Tiglian A transition in NW Europe (Fig. 4, Van Kolfschoten & Gibbard 1998, Zagwijn 1998).

This age estimate was based on foraminifer faunas that point to a Plio-Pleistocene age (Feyling-Hanssen 1990), reversed palaeomagnetism in the fine-grained part of the sequence, supporting correlation with the Matuyama Chron (Abrahamsen & Marcussen 1986), and amino acid analyses of bivalve shells giving ratios that fit with this age (see below). However, these methods leave wide margins of uncertainty, and an important argument in favour of the c. 2.4 ma age estimate was the coincidence of species with last and first appearance datum at c. 2.5 ma. These species were especially ostracodes and small mammals,
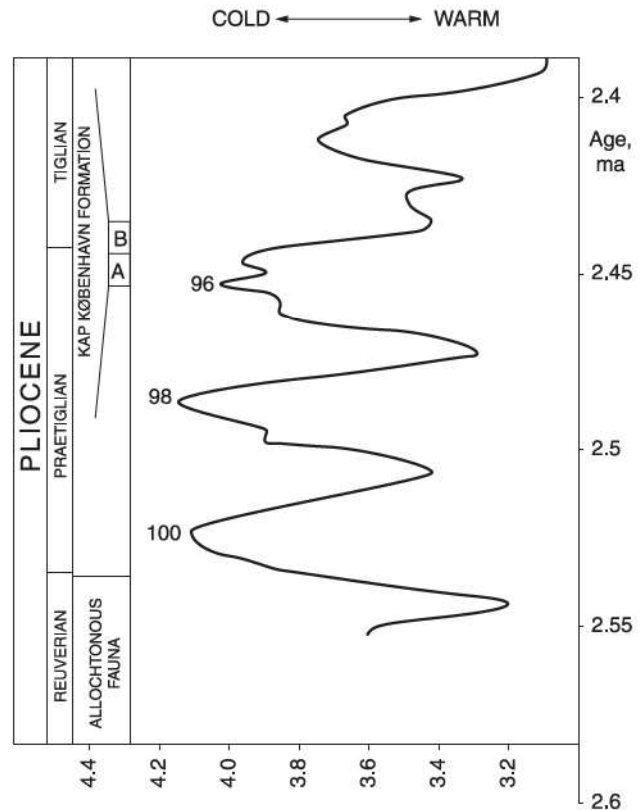

Fig. 4. Stratigraphy and age of the the Kap København Formation, compared with the orbitally tuned oxygen isotope record from ODP site 846, isotope stages 101-93 (Shackleton et al. 1995)

which were known from the Neogene of Alaska and Beringia (Repenning et al. 1987, Brouwers et al. 1991). However, McDougall (1995) questioned the accuracy in dating the first and last appearances of these little known animals, and suggested a much younger age for the Fishcreekian of Alaska.

The Fishcreekian is a likely correlative to The Kap København Formation and dated by similar techniques (Brigham-Grette & Carter 1992), and this uncertainty therefore also affects the dating of the Kap København Formation. However, there is still some evidence in favour of the 2.4 ma age. This comes from amino acid racemization in mollusc shells, even though the time resolution of this method is poor and does not allow precise dating (Wehmiller & Miller 2000). For the Kap København Formation 12 shells of *Mya truncata* and *Hiatella arctica* gave an average alloisoleucine:isoleucine ratio (aile:ile) of 0.135 ±0.032 in the total hydrolysate. Amino acid racemization is highly dependent on temperature, and with the age of 2.4 ma this would require an effective diagenetic temperature (EDT) of −14 ±1°C, when applying the Arrhenuis equation of Miller (1985). This estimate
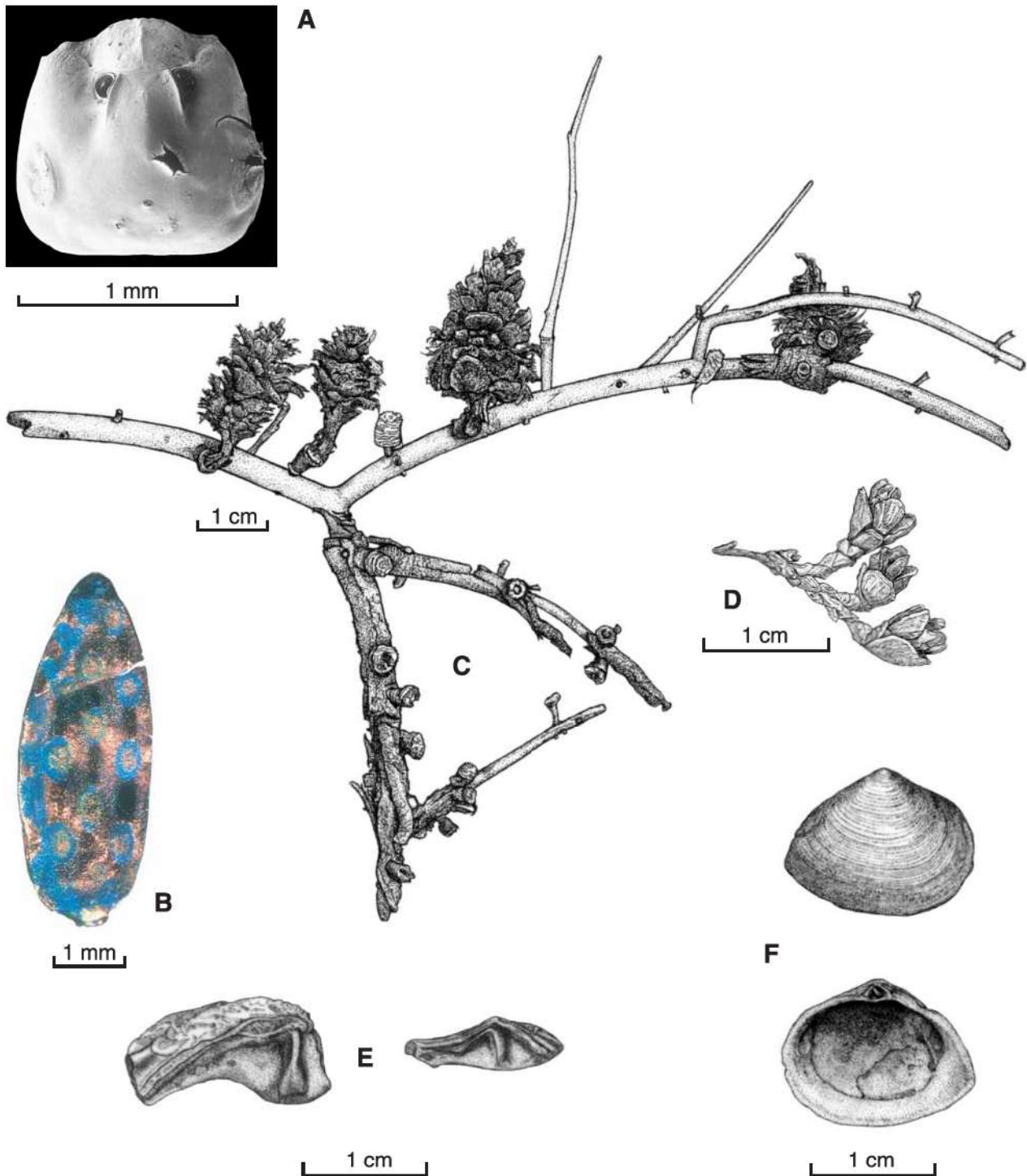
Fig. 5. Plant and animal remains from the Kap København Formation. A. Head of *Formica* sp., unit B3, loc. 77. Ants are not living in Greenland at present, and have not been found as fossils before. B: Elytron of the beetle *Elaphrus tuberculatus* with coloration preserved. Today the beetle lives on silt along large rivers. Unit B3, loc. 77. C: Twig of *Larix groenlandii*, Unit B3, loc. 127. The irregular branching testify to hard conditions. D: Twig of *Thuja occidentalis*, unit B3, loc. 122. *Thuja* prefers a humid climate with not too cold winters. Today it is not found at the northern treeline. E: *Arctica islandica* fragments from "allochthonous fauna", localities 10 and 33. F: *Macoma balthica,* unit B2, loc. 68. Strangely enough the finds at Kap København and its correlative the Fishcreekian of Alaska are the earliest record of this boreal brackish water bivalve. Sources: A, B: Böcher 1995. Photo G. Brovad. C, D: Bennike 1990. Drawing C. Rasmussen. E, F: Símonarson et al. 1998. Drawing C. Rasmussen

lends credibility to the 2.4 ma age because the calculated temperature is close to the present mean annual temperature of the area at –16°C. For the younger age of 1.7 ma, suggested by McDougall (1995) EDT would be –12 ±1°C.

Another, indication of the 2.4 ma age comes from the allochthonous fauna. This is an assemblage of heavily worn fragments of mollusc shells including the thermophilous *Arctica islandica* that is unknown from the in situ faunas (Fig. 5). The reworked fragments form a thin lag over the erosion surfaces above member A sediments. The uniformity of the fauna assemblage in all parts of the area indicates that it was reworked into member A from the same source, probably the same as the thermophilous foraminifers, which also occur in the glaciomarine sediment of member A (Feyling-Hanssen 1990). These include *Cibicides grossa*, a well-known representative of temperate benthic faunas until it became extinct at c. 2.5 ma (Fyles et al. 1998). The shell fragments in the allochthonous fauna have undergone at least two cycles of reworking and their temperature history must be different and more variable than that of the *in situ* shells in the Kap København Formation, as seen also in the large spread of ratios for these fragments, 0.250-0.143 for *Hiatella arctica* (Símonarson et al. 1998). Since reworking and exposure can only raise EDT, we consider the lowest aile:ile ratio as the most representative. This implies that there is no large age difference between the Kap København Formation and the allochthonous fauna, and the occurrence of *Cibicides grossa* shows that it is older than 2.5 ma and the Kap København Formation was deposited not long after this. Similar evidence is provided by the Sr-analyses, which show no significant difference between shells from the allochthonous fauna and from unit B (Appendix 2).

Therefore, we consider The Kap København Formation and the Fishcreekian as correlatives and slightly younger than the *Cibicides grossa* Zone (c. 2.5 ma), and we still find the age of c. 2.4 ma at the Praetiglian/Tiglian boundary the most trustworthy. As discussed below, this age also satisfies the requirements to isostasy and eustasy recorded in the sediments. We correlate the allochthonous fauna with the Reuverian in northern Europe. This was the warm stage before the Praetiglian ice age, which ended at c. 2.6 ma (van Kolfschoten & Gibbard 1998). In the arctic it is known from the recently described Hvitland beds of northern Canada, which contain both *Cibicides grossa* and *Arctica* (Fyles et al. 1998).

Environments

The Kap København Formation contains both *in situ* marine and river-transported terrestrial fossils, but the proportion of marine and terrestrial are complementary. The deep-water facies (member A and unit B2) have a strong marine and a weak terrestrial signal. The opposite is true for the shallow water facies (units B1, B3), which have yielded a rich terrestrial record contained in beds of mosses, especially *Scorpidium* and *Drepanocladus*, which probably were torn from river banks and washed or blown to the foreshore with their content of seeds, leaves, and insect remains (Fig. 5). The content of fossils in each unit is listed in Appendix 1.

The boundaries between units are based on sea-level change and not strictly synchronous over the region. This is indicated by the thickness of the deep-water unit B2 as noted above, suggesting that the duration of deep water period decreased landwards (Fig. 2).

The environmental record starts with the deglacial member A. The laminated clay is devoid of terrestrial remains, and the marine macro- and microbenthos contain, as mentioned above, older reworked organisms and therefore give a mixed environmental signal. However, the sparse *in situ* molluscs indicate arctic conditions with high sedimentation rates (Símonarson et al. 1998). After this, member B's shoreface sand and bioturbated mud (unit B1 and lower B2) is in the central part of the area characterised by a low diverse *Cyrtodaria-Portlandia* assemblage. This is a close parallel to estuarine-arctic biocoenoses in coastal brackish waters of northern Siberia (Gukov 1996, Petryashov et al. 1999). Reduced salinity is also indicated by the ostracode fauna and Sr-analyses (Appendix 2). However, the upper shoreface sediments at inland localities contain a littoral fauna with abundant *Macoma balthica* (Fig. 5) similar to present conditions at the subarctic-arctic boundary such as the Baydarats Gulf in western Siberia (Filatova & Zenkevich 1957, Kucheruk *et al.* 1998), showing that sea surface temperatures had risen to warmer than present. The *Cyrtodaria-Portlandia* biocoenosis may thrive under permanent sea ice cover, whereas the *Macoma balthica* biocoenosis requires seasonally open water.

At the same time the land became covered by rich dwarf shrub heaths with abundant *Betula nana*, *Vaccinium uliginosum* and *Empetrum nigrum*, similar to present conditions in Greenland c. 500 km to the south of Kap København. Trees and shrubs were as yet absent, except for the extinct shrub *Myrica arctogale* (Bennike 1990). Low arctic conditions are indicated also by the insect fauna reflecting dry climate in the early part of the interglacial (Böcher 1995).

The culmination of ecosystem diversity was reached together with the sea-level highstand (upper unit B2 and B3), as is usually the case in an interglacial. Trees now reached the shores of the Arctic Ocean, 1000 km to the north of the world's northernmost trees today. The cones, twigs, seeds, leaves and wood show that there were five species of trees (Bennike 1990). Dominant was the extinct *Larix groenlandii* (Fig. 5), accompanied by *Thuja occidentalis, Picea mariana, Betula alba,* and *Taxus.* In between the trees were tall shrubs of *Cornus, Salix, Myrica, Viburnum,* and *Alnus.* Also the insects testify to forest tundra conditions with 14% of the identified species being more or less obligate forest species. Among them the carpenter ant, *Camponotus herculeanus,* living in shaded forests and nesting in rotten stumps and logs (Böcher 1995).

The mammals which lived in this environment have unfortunately left only very few traces: remains of *Lepus* and *Hypolagus,* hare droppings and remains of *Aphodius* beetles, which live in and from mammalian dung (Bennike 1990, Böcher 1995).

However, the trees in the tundra were small, slow growing, and stunted, and the area was at the tree line, with trees growing only on favourable spots in an area dominated by heath (Bennike 1990). Both insects and plants indicate that now the climate had changed to humid.

Although the marine fauna also peaked in this interval, the change is less impressive. Among the "warm" newcomers were *Nucula nucleus, Rissoa parva,* and *Pseudosetia turgida,* and at the foreshore *Macoma balthica* was still abundant. The low diversity of the fauna may to some extent reflect reduced salinity. However, the find of only a single individual of the gregarious *Mytilus edulis* underlines the fact that the marine environment was still quite cool, and the shores of Northeast Greenland were probably washed by cold Polar water from the East Greenland Polar Current as they are today.

At one locality (no. 17), unit B3 possibly attains a thickness of 40 m, and the plant remains in the upper parts may indicate a cooling and return to heath conditions (Bennike 1990), but at all other localities the record stops in the forest-tundra period, indicating that regression and sediment bypass began at this time, as also seen in the record of ice sheet marginal areas during later interglacials.

In conclusion, both the terrestrial and marine records show that changes in relative sea-level were accompanied by a development from cold to warmer conditions typical of an interglacial, but the change on land was much more spectacular than in the shallow marine environment. On land there was change from arctic to boreal, while the shallow water ecosystems changed from arctic to arctic with subarctic elements. The record ends with the attainment of sea-level highstand and of optimal diversity of the ecosystems.

Climate

Bennike (1990) and Böcher (1995) discussed the terrestrial climate on the basis of plants and insects, while Brouwers et al. (1991) and Símonarson et al. (1998) dealt with the coastal water temperatures from ostracodes and molluscs. This has lead to a variety of temperature estimates, especially for the summer warmth during the climate optimum both on land and in the sea (Table 1). The variability lies especially in the values derived from insects and ostracodes, and is not only between sites and samples, but also within single samples (Brouwers et al. 1991, Böcher 1995). When statistical methods such as MCR (Mutual Climatic Range method) and transfer functions are applied to the faunas, two distinctly different temperature regimes may be found in the same sample, an arctic and a boreal, with no mutual species-overlap today. The derived summer temperatures may reach 19° and 18° for land and sea - comparable to the warm-temperate southern Europe today. These temperatures are unrealistic when compared to the general fauna and vegetation and the exercise shows that the statistical methods cannot be used on Neogene Arctic land and shallow water faunas, and underline the no-analogue character of the fauna and flora, as noted by Brouwers et al. (1991).

The values in Table 1 are based on the general assessment of the flora and fauna. As noted above, the stunted and slow growing trees indicate tree-line conditions with mean temperatures for the warmest month of c. 10°, and both *Thuja* and *Taxus* are sensitive to cold winters with mean temperatures below –17° (Bennike 1990). This range, from c. 10 to –17°, does not exclude permafrost in the area, which may occur when mean annual temperatures are below –4 – –5°C. Incorporation in permafrost shortly after burial seems to be a prerequisite for the extraordinary preservation of delicate insect and plant remains, which is so unique in the Kap København Formation.

Both plants and insects indicate that precipitation at the climate optimum was in excess of 500 mm/yr and snow fall during the winter was heavy, as seen from the branch-structure of the trees (Bennike 1990). However, there are also insects and plants from more arid climates, possibly coming from interior parts of the area (Böcher 1995). The temperature records show that the most marked deviation from present climate was the much milder winters.

We consider the shallow marine benthic fauna to reflect sea surface temperatures. Modern equivalents to the mollusc fauna indicate an annual range from c. 0° to c. 3–5° and 8–9 months sea ice coverage (Zenkevitch 1963, Símonarson et al. 1998). Higher summer temperatures may have been attained locally in areas with large supply of river runoff.

Other Greenland sites

Foraminifer faunas in the Lodin Elv Formation on Jameson Land contain *Cibicides grossa* and *Cassidulina teretis* suggesting that it is older but overlapping with the Kap København Formation (Fig. 1, Feyling-Hanssen et al. 1983). This site has only been visited briefly in 1978, and the age is in need of verification by modern methods.

On Île de France marine sediments have yielded amino acid ratios indicative of considerable age (Landvik 1994), and a mollusc fauna containing *Arctica islandica* (Bennike & Weidick 1998). Although there are faunal similarities (*Nucula nucleus, Trichotropis bicarinata*), the differences seem more prominent, and these deposits are probably older than the Kap København Formation.

In northern Greenland, driftwood with non-finite ^{14}C-age has been encountered at a number of sites, reworked into younger sediments (Bennike 1998, 2000). Narrow growth rings indicate tree-line conditions, and from the species composition Bennike (1998) suggested an age of c. 3 ma for some of the wood.

Discussion

Naish (1997) and Pillans et al. (1998) demonstrated that in the Late Neogene and Early Pleistocene 6th order (41 kyr) glacioeustatic cycles was the dominant force in sea-level change. During the first period of major Cenozoic ice sheets (isotope stages 100–96) the glacioeustatic sea-level oscillations may have amounted to more than 100 m, and the melting of the Praetiglian ice sheets (isotope stage 96–95) probably caused sea-level to rise 78 ±20 m or more (Naish 1997). We suggest that the Kap København Formation was laid down during this period, but the sea-level rise was to some extent compensated by isostatic rebound. A major Praetiglian ice sheet over northern Greenland is indicated also by the IRD (ice rafted detritus) record from the adjacent Fram Strait, which has one of its most distinct peaks at c. 2.5 ma (Thiede et al. 1998).

In the "41 kyr period" the ice volume/insolation relation was almost linear (Muller & McDonald 1997), and the deglaciation process and eustatic rise probably less abrupt than in later interglacials. We therefore estimate the duration of the sedimentation to have lasted a half obliquity cycle, i.e. 20,000 yr, at the most.

The duration of sedimentation of the Neogene marine sediments has rarely been discussed in earlier publications. However, in their correlation charts most authors assign durations of 100,000 yr or more to the Kap København Formation and its North American correlatives (Repenning et al. 1992, Brigham-Grette & Carter 1992, Penney 1993, McDougall 1995). Although not specifically discussed, an argument for this seems to lie in the foraminifer stratigraphy, which was engineered by Feyling-Hanssen (1976, 1990), and used for correlating sites in Alaska, Canada and Greenland (e.g. McDougall 1995, Fyles et al. 1998).

Table 1, Late Pliocene climate during the climate optimum (unit B3) of the Kap København, compared to the present

Evidence	Mean temperature of warmest month, °C	Mean temperature of coldest month, °C	Mean annual temperature, °C	Precipitation, mm/yr	Continuous permafrost	Coastal sea surface temperature, summer, °C	Coastal sea surface temperature, winter, °C	Duration of sea ice cover, months
Vegetation (Bennike 1990)	10–11	−10 – −15		≥500				
Insects (Böcher 1995)	c. 15	c. −10						
Ostracodes (Brouwers et al. 1991)						9–12	−2	
Molluscs, analogy with present biota						4–5	≈0	8–9
This work	c. 10	c. −17	c. −4	≥500	probably	4–5	≈0	8–9
Now*	3	−31	−17	200	yes	0	0	12

*1961–1990 at Nord, 115 km SE of Kap København (Danish Meteorological Institute 2001)

This stratigraphy is based on speciation in response to Neogene-Pleistocene climatic cooling and considered to be circum arctic (Feyling-Hanssen 1990). In the Kap København Formation Feyling-Hanssen (1990) found six successive foraminifer zones in the fine grained Member A and unit B2. It is unlikely that this speciation and faunal evolution could have taken place in less than 20,000 yr. Also, Feyling-Hanssen (1990) found correlation between sites within the area difficult and suggested a temporal succession between sites, which from their lithology and other fauna remains would have been thought to be contemporaneous. The longer duration implied by these data would call for a more complex model of the local sedimentation, comprising successive phases of incision and infilling with similar sedimentary facies. Although no signs of this have been discovered in the field it is certainly a possibility, which cannot be ruled out and should be considered in future fieldwork. However, four of the foraminifer zones occur in one section (locality 50). In this section sediments as well as faunas and floras reflect major climatic and environmental change over time, and we suggest that the succession of foraminifer faunas could reflect this and not evolution. Local variations in depth and salinity could possibly also explain the faunal differences between sites within the area, as indicated by the mollusc faunas.

On balance, therefore, we find the arguments for a short duration stronger than those against it, and favour an estimate of less than 20,000 years for the Kap København Formation.

Greenland in the Late Pliocene

By extrapolation and imagination the inferred climatic parameters can be used to paint a picture of Greenland's appearance at the climate optimum of the Kap København Formation (Fig. 6). The topographical base is Letréguilly et al.'s (1991) map of the subglacial topography after isostatic relaxation. The north-south climatic gradient is calculated by comparison with terrestrial data from the Tiglian of northern Europe (Zagwijn 1974, Pross et al. 2000), and the general distribution of vegetation and lapse rate are based on present-day conditions.

With summer temperatures of more than 10°C at Greenland's northern tip it is inconceivable that the Greenland ice sheet could have existed at the peak of the interglacial warmth (Letréguilly et al. 1991), and Greenland is envisaged as a land of boreal forests with heaths and tundra on the uplands. Along the mild and humid western coast and in the lowlands around

Fig. 6. Greenland in the Late Pliocene, based on information from The Kap København Formation and seismics and borings along the coasts. (From Funder 1996)

the large river draining into Disko Bugt there were possibly deciduous forests, but the high mountains in humid south-east Greenland may well have been covered by local ice caps. Coring off the shelf has shown that this area has a glaciation record going back into the Late Miocene (Larsen et al. 1994).

The reconstruction shows Greenland as a fjord country already at this early time, implying that active glaciers had been eroding the country long before. This is based on the location of the Kap København Formation and the Kap Rigsdagen occurrence

on both sides of Independence Fjord, showing that the fjord or at least an embayment existed here. Similar evidence has been obtained from Scoresby Sund where Pliocene marine sediments occur at the side of the fjord, a good distance from the outer coast (Feyling-Hanssen et al. 1983). Also, seismic work along the east coast of Greenland has indicated northern Greenland as a nucleus for northern hemisphere glaciation with glaciers coming down to the sea as early as the Middle Miocene at 14 ma (Thiede et al. 1998), and "middle sized ice sheets" reaching the shelf margin at several stages during the Early Pliocene (Solheim et al. 1998, Channell et al. 1998, Clausen 1998, Butt et al. in press).

Acknowledgement

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Appendix 1

Plant and animal remains from the Kap København Formation
Remains of plants, foraminifers, bryozoans, ostracodes, molluscs, cladocers, insects and vertebrates and their distribution in sedimentary units. Also the plants and molluscs at Kap Rigsdagen and the molluscs of the "allochthonous fauna" are shown. Taxa marked with * are extinct, all other are extant.
Compiled from Bennike 1990, Brouwers et al. 1991, Böcher 1995, Feyling-Hanssen 1990, Fredskild & Røen 1982, Mogensen 1984, Penney 1993, Repenning et al. 1987, Røen 1988, Símonarson et al. 1998.
1) – Allochthonous fauna – 2) – Kap Rigsdagen

Members and units	A	B1	B2	B3	1)	2)
PLANTS						
Thallophyta (Bennike 1990) Bacteria						
Proactinomyces alni (Peklo) Krass				x		
Algae						
Tolypella cf. *nidifica* (O. Müll.) A. Br.				x		
Fungi						
Cennococcum geophilum Fries		x	x	x		
Bryophyta (Mogensen 1984)						
Cinclidium arcticum (B.S.G.) Schimp		x				
Cinclidium stygium Sw.						
Cyrtomnium hymenophylloides (Hüb.) T. Kop.			x			
Cyrtomnium hymenophyllum						
(B.S.G) Holmen		x				
Distichum sp.				x		
Ditrichum flexicaule (Schwaegr.) Hampe				x		
Drepanocldus exannulatus (B.S.G) Warnst.				x		
Mnium thomsonii Schimp.		x				
Orthothecium sp.				x		
Plagiomnium medium ssp. *curvatulum*						
(Lindb.) T. Kop.		x				
Polytrichum sp.				x		
Scorpidium scorpioides (Hedw.) Limpr.		x		x	x	
Sphagnum sp.		x				
Pteridophyta (Bennike 1990)						
Selaginella selaginoides (L.) Link				x		
Gymnosperma (Bennike 1990)						
Picea mariana (Mill.) B.S.P.				x		
Larix groenlandii Bennike*				x		
Thuja occidentalis L.				x		
Taxus sp.				x		
Angiospermae (Bennike 1990)						
Nuphar lutea tp.				x		
Ranunculus hyperborea tp.				x		
Ranunculus cf. *pallasii* Schlecht		x		x		
Anemone sp.						
Papaver sect. *Scapiflora* Reichenb.				x		
Betula nana L.		x	x	x		
Betula alba L. s.l.				x		
Alnus cf. *crispa* (Ait.) Pursh.				x		
Oxyria digyna (L.) Hill.		x	x	x		
Polygonum sp.				x		
Rumex acetosa L.		x		x		
Cerastium cf. *arcticum* Lge./*alpinum* L.				x		
Stellaria sp.				x		
?Arenaria sp.				x		
Melandrium affine J. Vahl/*angustiflorum*						
(Rupr.) Walp.				x		
Viola sp.				x		
Arabis cf. *alpina* L.			x			
Salix reticulata L.				?		

Members and units	A	B1	B2	B3	1)	2)
Salix spp.		x	x	x		
Myrica arctogale* Bennike		x	x	x		
Arctostaphylos uva-ursi (L.) Spreng.				x		
Cassiope tetragona (L.) D. Don				?		
Ledum palustre L.				x		
Andromeda polifolia L.		x		x		
Oxycoccus palustris L.				x		
Vaccinium uliginosum L. *microphyllum* Lange			x	x	x	
Empetrum nigrum L. s.l.		x	x	x		
Sedum annuum L.				x		
Hedysarum sp.				x		
Potentilla spp		x	x	x		
Potentilla palustris (L.) Scop.				x		
Dryas octopetala L.		x	x	x		
Rubus chamaemorus L.				x		
Rubus arcticus L./*saxatilis* L.				x		
Hippuris vulgaris L.			x	x		
Erodium sp.				x		
Cornus stolonifera Michx.				x		
Cornus canadensis L.				x		
Cornus sp. A				x		
Menyanthes trifoliata L.		x	x	x		x
Viburnum cf. *edule* (Michx.) Raf.				x		
?Linaria sp.				x		
Potamogeton natans L.		x	x	x		
Potamogeton cf. *perfoliatus* L./						
richardsonii (Benn.) Rydb.				x		
Potamogeton cf. *gramineus* L.				x		
Potamogeton alpinus Balb.				x		
Potamogeton cf. *vaginatus* Turcz.			x	x		
Juncus sp.				x		
?Luzula sp.				x		
Carex spp.		x	x	x		
Carex cf. *chordorrhiza* Ehrh.				x		
Sparganium angustifolium tp.				x		
Aracites globosa* (Reid & Reid) Bennike				x		
FORAMINIFERA						
(Feyling-Hanssen 1990)						
Ammodiscus cf. *concinnus* Kuznetzova			x			
Textularia cf. *canaensis* Bermudez	x					
Trochammina sp.			x			
Quinqueloculina lamarckiana d´Orbigny	x					
Quinqueloculina longa Gudina	x		x			
Quinqueloculina obliquecamerata						
Grigorenko	x					
Quinqueloculina parkeri (Brady)	x					
Quinqueloculina seminulum (Linné)	x		x			
Triloculina tricarinata d'Orbigny			x			
Pyrgo simplex (d'Orbigny)			x			
Pyrgo williamsoni (Silvestri)			x			
Scutuloris pyriformis (Gudina)			x			
Miliolinella enoplostoma (Reuss)				x		
Miliolinella subrotunda (Montagu)			x	x		
Miliolinella valvulinaris (Reuss)			x			
Guttulina austriaca d'Orbigny	x		x			
Guttulina dawsoni Cushman & Ozawa			x			
Guttulina lactea (Walker & Jacob)	x					
Guttulina orientalis Cushman & Ozawa			x			
Guttulina roemeri (Reuss)	x		x			
Pyrolina cylindroides (Roemer)		x	x			
Globulina cf. *granulosa* Egger		x	x			
Globulina inequalis Reuss			x			
Globulina minuta (Roemer)			x			
Pseudopolymorphina decora (Reuss)			x			
Pseudopolymorphina dollfussi						
Cushman & Ozawa		x	x			
Polymorphina charlottensis Cushman			x			
Glandulina laevigata d'Orbigny			x			
Esosyrinx curta (Cushman & Ozawa)			x			
Cassidulina laevigata d'Orbigny	x					
Cassidulina reniforme Nørvang	x	x	x	x		
Cassidulina teretis Tappan*	x					
Cassidulina cf. *teretis* Tappan*			x			
Stainforthia loeblichi (Feyling-Hanssen)			x			
Eoponidella pulchella (Parker)		x				
Bucella frigida (Cushman)	x	x	x	x		
Bucella hannai arctica Voloshinova			x			
Bucella tenerrima (Bandy)		x	x	x		
Glabratella wirghtii (Brady)			x			

Members and units	A	B1	B2	B3	1)	2)
Epistominella vitrea Parker	x	x	x			
Cibicides grossa Ten Dam & Reinhold*	x					
Pullenia subcarinata (d'Orbigny)			x			
Melonis barleeanus (Williamson)	x		x	x		
Melonis eurocopsis (Todd)	x					
Haynesina matchigaricus (Voloshinova)	x	x	x			
Haynesina nivea (Lafrenz)		x	x	x		
Haynesina orbiculate (Brady)	x	x	x	x		
Nonionella lobsannensis (Andreae)	x					
Astrononion gallowayi Loeblich & Tappan			x			
Elphidium albiumbilicatum (Weiss)		x	x	x		
Elphidium asklundi Brotzen				x		
Elphidium bartletti Cushman				x		
Elphidium excavatum (Terquem)	x	x	x	x		
Elphidium cf. *excavatum* (Terquem)	x	x	x			
Elphidium funderi Feyling-Hanssen	x					
Elphidiella tumida Gudina, not *Elphidiella groenlandica* Cushman				x		
Elphidium hallandense Brotzen			x			
Elphidium hughesi Cushman & Grant	x	x	x			
Elphidium subglobosum (Voloshinova)	x					
Elphidium ustulatum Todd*		x	x	x		
Elphidiella gorbunovi (Stschedrina)		x	x	x		
Elphidiella hannai (Cushman & Grant)		x	x	x		
Elphidiella rolfi (Gudina & Polovova)	x	x	x	x		
Globigerina pachyderma (Ehrenberg)				x		

BRYOZOANS (Bennike 1990)

Members and units	A	B1	B2	B3	1)	2)
Cristatella mucedo Cuvier, 1798		x		x		

OSTRACODES (Brouwers *et al.* 1991, Penney 1993)

Members and units	A	B1	B2	B3	1)	2)
Baffinicythere sp.			x			
Bythocythere sp.	x					
Cytheretta teshekpukensis Swain 1963	x		x	x		
Cytheromorpha macchesneyi (Brady & Crosskey, 1871)	x	x	x	x		
Cytheromorpha cf. *knikensis* Forrester & Brouwers 1985			x			
Cytheropteron champlainum Cronin 1981			x	x		
Cytheropteron cf. *montrosiense* Brady, Crosskey & Robertson, 1874	x		x	x		
Cytheropteron cf. *occultum* Whatley & Masson 1979			x			
Cytheropteron paralatissimum Swain 1963	x		x			
Cytheropteron pseudomontrosiense Whatley & Manson 1979	x					
Cytheropteron simplex Whatley & Manson 1979	x					
Cytheropteron cf. *subcircinatum* Sars 1966	x					
Cytheropteron tumefactum Lev. 1972			x	x		
Cytheropteron sp. 1		x	x			
Cytheropteron sp. 2				x		
Cytheropteron sp. 3			x			
Cytheropteron sp. 4				x		
Cytheropteron sp. 5				x		
Cytheropteron sp. 6			x			
Cytheropteron sp. 7	x					
Cytheropteron sp. 8	x		x			
Cytheropteron sp. 9	x		x			
Elofsonella neoconcinna Bassiouni 1965	x					
Eucythere? sp.	x					
Finmarchinella angulata (Sars, 1866)			x			
Heterocyprideis fascis (Brady & Norman, 1889)	x			x		
Heterocyprideis sorbyana (Jones, 1857)	x	x	x	x		
Jonesia sp.			x			
Krithe cf. *glacialis* Brady, Crosskey & Robertson, 1874		x				
Krithe sp.			x			
Leptocythere sp.				x		
Loxoconchai? sp. 1			x			
Loxoconchai? sp. 2			x			
Palmenella limicola (Norman, 1865)			x			
Palmoconcha venepidermoidea (Swain 1963)	x		x	x		
Paracyprideis pseudopunctillata Swain 1963			x	x		
Paracytheridea sp.			x			
Pontocythere sp.			x			
Pteroloxa venepuncta Swain 1963			x			

Members and units	A	B1	B2	B3	1)	2)
Pterygocythereis vannieuwenhuisei Brouwers 1987*			x	x		
Rabilimis mirabilis (Brady, 1868)	x					
Rabilimis paramirabilis (Swain 1963)*	x	x	x	x		
Rabilimis septentrionalis (Brady, 1866)		x	x			
Robertsonites tuberculatus (Sars, 1866)		x	x	x		
Sarsicytheridea bradii (Norman, 1865)			x	x		
Sarsicytheridea macrolaminata (Elofson 1939)				x	x	
Sarsicytheridea punctillata (Brady, 1865)	x	x	x	x		
Sarsicytheridea n. sp.			x			
Semicytherura complanata (Brady, Crosskey & Robertson, 1874)			x			
Semicytherura sp.				x		
Semicytherura sp. 2			x			
Tetracytheura sp.			x			

CLADOCERS (Røen 1988)

Members and units	A	B1	B2	B3	1)	2)
Daphnia pulex Leydig				x		
Simocephalus cf. *vetulus*				x		
Cerodaphnia cf. *quadrangula*				x		
Bosmina longirostris (O.F. Müller)				x		
Eurycercus glacialis *Liljeborg*				x		
Alona cf. *affiinis*				x		
Alona *cf.* guttata				x		
Alona cf. *costata*				x		
Alona cf. *rectangula*				x		
Alonella cf. *excisa*				x		
Pleuroxus cf. *striatus*				x		
Chydorus sphaericus/arcticus				x		

INSECTS (Böcher 1995)
Carabidae

Members and units	A	B1	B2	B3	1)	2)
Trachypachus zetterstedtii (Gyllenhal, 1827)				x		
Nebria cf. *rufescens* (Ström, 1768)				x		
Nebria cf. *nivalis* (Paykull, 1790)				x		
Opisthius richardsoni Kirby, 1837				x		
Notiophilus aquaticus (Linnaeus, 1758)		x		x		
Notiophilus cf. *biguttatus* (Fabricius, 1779)				x		
Cicindela cf. *hybrida* Linnaeus, 1758				x		
Blethisa multipunctata (Linnaeus, 1758)				x		
Blethisa catenaria Brown 1944				x		
Diacheila polita (Falderman, 1835)				x		
Diacheila matthewsi Böcher 1995				x		
Elaphrus lapponicus Gyllenhal, 1810				x		
Elaphrus sibiricus Motschulsky, 1846				x		
Elaphrus cf. *olivaceus* LeConte, 1863				x		
Elaphrus lecontei Crotch, 1876				x		
Elaphrus tuberculatus Mäklin, 1877		x	x	x		
Elaphrus angusticollis F. Sahlberg, 1844				x		
Dyschirius cf. *varidens* Fall 1910				x		
Miscodera arctica (Paykull, 1798)				x		
Patrobus stygicus Chaudoir, 1871				x		
Asaphidion alaskanum Wickham 1919				x		
Bembidion levettei Casey 1918				x		
Bembidion alaskense Lindroth 1962				x		
Bembidion cf. *velox* (Linnaeus, 1761)		x		x		
Bembidion cf. *lapponicum* Zetterstedt, 1828				x		
Bembidion cf. *balli* Lindroth 1962				x		
Bembidion cf.*vitiosum* Gemminger & Harold, 1868				x		
Bembidion dyschirinum LeConte, 1861		x		x		
Bembidion lampros Herbst, 1784				x		
Bembidion cf. *fellmanni* Mannerheim, 1823		x	x	x		
Bembidion cf.*difficile* (Motschulsky, 1844)				x		
Bembidion cf.*arcticum* Lindroth 1963		x		x		
Bembidion planatum LeConte, 1848				x		
Bembidion cf. *planiusculum* Mannerheim, 1843		x		x		
Bembidion cf. *gebleri* Gebler, 1833		x		x		
Bembidion salebratum LeConte, 1848				x		
Bembidion cf. *mckinleyi* Fall 1926				x		
Bembidion cf. *lenae* Csiki 1928		x				
Bembidion cf. *grapii* Gyllenhal, 1827				x		
Bembidion cf. *yukonum* Fall 1926		x		x		
Bembidion cf. *bimaculatum* Kirby, 1837		x		x		
Bembidion cf. *sordidum* Kirby, 1837		x	x	x		
Pterostichus stygicus Say, 1823				x		
Pterostichus nigrita (Paykull, 1790) *s.l.*				x		
Pterostichus cf. *corvinus* Dejean, 1828				x		
Pterostichus cf. *caudicalis* Say, 1823				x		

Members and units	A	B1	B2	B3	1)	2)
Pterostichus cf. *arcticola* Chaudoir, 1868				x		
Pterostichus cf. *planus* J. Sahlberg, 1887				x		
Pterostichus cf. *pinguedineus* Eschscholtz, 1823				x		
Pterostichus riparius Dejean, 1829				x		
Pterostichus brevicornis Kirby, 1837	x			x		
Pterostichus vermiculosus Ménétries, 1851			x	x		
Pterostichus cf. *agonus* Horn, 1880				x		
Pterostichus haematopus Dejean, 1831				x		
Agonum cf. *consimile* Gyllenhal, 1810				x		
Agonum cf. *exaratum* Mannerheim, 1853				x		
Amara cf. *apricaria* (Paykull, 1790)				x		
Amara cf. *glacialis* Mannerheim, 1853				x		
Amara cf. *quenseli* (Schönherr, 1806)				x		
Amara cf. *brunnea* (Gyllenhal, 1810)				x		
Amara cf. *pseudobrunnea* Lindroth 1968				x		
Chlaenius cf. *interruptus* Horn, 1876				x		
Dromius cf. *angusticollis* J. Sahlberg, 1880				x		
Noteridae						
Noterus crassicornis (Müller, 1776)				?		
Dytiscidae						
Hydroporus cf. *morio* Aubé, 1838				x		
Hydroporus cf. *striola* Gyllenhal, 1827				x		
Oreodytes cf. *sanmarkii* (Sahlberg, 1826)				x		
Oreodytes alpinus (Paykull, 1798)/*laevis* Kirby, 1837			x	x		
Agabus cf. *affinis* (Paykull, 1798)				x		
Agabus clavicornis Sharp, 1882/*serricornis* Paykull, 1799				x		
Agabus bifarius (Kirby, 1837)				x		
Agabus cf. *anthracinus* Mannerheim, 1852				x		
Ilybius vittiger (Gyllenhal, 1827)				x		
Hydrophilidae						
Helophorus cf. *khnzoriani* Angus 1970				x		
Helophorus tuberculatus Gyllenhal, 1808				x		
Megasternum obscurum (Marsham, 1802)				?		
Leiodidae						
Agaricophagus cephalotes Schmidt, 1841				x		
Anisotoma cf. *castanea* (Herbst, 1792)				x		
Silphidae						
Thanatophilus baicalicus Motschulsky, 1860				x		
Heterosilpha ramosa (Say, 1823)				x		
Agyrtidae						
Pteroloma forsstromii (Gyllenhal, 1810)	x			x		
Staphylinidae						
Stenus melanarius Stephens, 1833				x		
Stenus cf. *canaliculatus* Gyllenhal, 1827				x		
Stenus vinnulus Casey, 1884				x		
Stenus assequens Rey, 1884	x					
Stenus hyperboreus J. Sahlberg, 1876				x		
Stenus cf. *carbonarius* Gyllenhal, 1827				x		
Stenus pubescens Stephens, 1843	x					
Stenus cf. *pinguis* Casey, 1884				x		
Stenus sordidus Puthz 1988				x		
Stenus cf. *mammops* Casey, 1884				x		
Stenus scrupeus Casey, 1884				x		
Stenus(*) n. sp.?	x			x		
Kalissus nitidus LeConte, 1874				x		
Pycnoglypta cf. *lurida* (Gyllenhal, 1813)	x			x		
Micralymma cf. *brevilingue* Schiödte, 1845				x		
Olophrum boreale (Paykull, 1792)				x		
Olophrum consimile (Gyllenhal, 1810)				x		
Olophrum cf. *rotundicolle* (Sahlberg, 1830)				x		
Eucnecosum cf. *tenue* (LeConte, 1863)				x		
Eucnecosum cf. *brunnescens* (J. Sahlberg, 1871)					x	
Eucnecosum n.sp ? *						
Acidota quadrata (Zetterstedt, 1838)				x		
Coryphium angusticolle Stephens, 1834				x		
Bledius cf. *litoralis* Heer, 1839				x		
Bledius cf. *arcticus* J. Sahlberg, 1890	x			x		
Bledius cf. *talpa* (Gyllenhal, 1810)				x		
Tachyporus cf. *rulomus* Blackwelder 1936	x					
Tachyporus cf. *borealis* Campbell 1979	x					
Tachinus elongatus Gyllenhal, 1810				x		
Scarabaeidae						
Aegialia terminalis Brown 1931				x		
Cantharidae						
Podabrus cf. *alpinus* (Paykull, 1798)				x		
Elateridae						
Hypnoidus rivularius Gyllenhal, 1808				x		

Members and units	A	B1	B2	B3	1)	2)
Byrrhidae						
Simplocaria cf. *metallica* (Sturm, 1807)				x		
Simplocaria cf. *elongata* J. Sahlberg 1903				x		
Simplocaria basalis J. Sahlberg 1903				x		
Morychus cf. *aeneus* (Fabricius, 1775)				x		
Arctobyrrhus subcanus (LeConte, 1878)				x		
Curimopsis cf. *moosilauke* Johnson 1986				x		
Derodontidae						
Laricobius cf. *caucasicus* Rost, 1893				x		
Anobiidae						
Cacotemnis cf. *carinatus* (Say, 1823)				x		
Coccinellidae						
Calvia quatuordecimguttata (Linnaeus, 1758)				x		
Myrrha octodecimguttata (Linnaeus, 1758)				x		
Colydiidae						
Orthocerus clavicornis (Linnaeus, 1758)				x		
Chrysomelidae						
Hydrothassa cf. *hannoveriana* (Fabricius, 1775)				x		
Chrysomela populi Linnaeus, 1758				x		
Curculionidae						
Cyriophthalmus variegatus (Motschulsky, 1846)				x		
Sitona cf. *ovipennis* Hochhuth, 1851				x		
Grypus equiseti (Fabricius, 1775)			x	x		
Grypus cf. *brunneirostris* (Fabricius, 1792)				x		
Notaris cf. *acridulus* (Linnaeus, 1758)				x		
Dorytomus cf. *imbecillus* Faust, 1882				x		
Pseudostyphlus pillumus (Gyllenhal, 1836)				x		
Anoplus cf. *plantaris* (Naezen, 1794)				x		
Rhyncolus cf. *brunneus* Mannerheim, 1843				x		
Magdalis cf. *violacea* (Linnaeus, 1758)				x		
Lepyrus cf. *arcticus* Paykull, 1792				x		
Litodactylus leucogaster (Marsham, 1802)				x		
Micrelus cf. *ericae* (Gyllenhal, 1813)				x		
Scolytidae						
Tomicus piniperda (Linnaeus, 1758)				x		
Scolytus piceae (Swaine 1934)				x		
Trypophloeus cf. *bispinulus* Eggers 1927				x		
HYMENOPTERA						
Siricidae						
Urocerus cf. *gigas* (Linnaeus, 1758)				x		
Formicidae						
Camponotus cf. *herculeanus* (Linnaeus, 1758)				x		
DIPTERA						
Chironomidae						
Corynocera ambigua Zetterstedt, 1840				x		
TRICHOPTERA						
Hydropsychidae						
Arctopsyche ladogensis (Kolenati, 1859)				x		
Hydropsyche nevae Kolenati, 1858				x		
Phryganeidae						
Agrypnia pagetana Curtis, 1835				x		
Agrypnia straminea Hagen, 1873				x		
Banksiola cf. *crotchi* Banks 1944				x		
Brachycentridae						
Brachycentrus americanus Banks, 1899				x		
Limnephilidae						
Apatania crymophila McLachlan, 1880				x		
Apatania cf. *nigra* Walker, 1852				x		
Halesochila taylori (Banks 1904)				x		
Dicosmoecus obscuripennis Banks 1938				x		
HEMIPTERA						
Pentatomidae						
Eusarcoris punctatus (Linnaeus, 1758)				x		
Drepanosiphidae						
Chaitophorus cf. *salijaponicus* Mordvilko 1929				x		
MOLLUSCS (Símonarson *et al.* 1998)						
Margarites sp.			x			
Pseudosetia turgida (Jeffreys, 1870)			x			
Boreocingula globula (Møller, 1842)		x	x			
Alvania sp.			x			
Rissoa parva (da Costa, 1778)			x			
Trichotropis bicarinata (Sowerby, 1825)				x		
Euspira pallida (Broderip & Sowerby, 1829)		x	x	x		
Lunatia sp.			x			
Natica affinis (Gmelin, 1790)	x			x		
Natica sp.	x	x	x			x

Members and units	A	B1	B2	B3	1)	2)
Trophon truncatus (Ström, 1767)				x		
Colus sp.				x		
Buccinum cf. *undatum* Linné, 1758			x	x		
Buccinum spp.			x			
Admete viridula (Jay, 1839)			x			
Oenopota decussata (Couthouy, 1839)		x	x	x		
Oenopota reticulata (Brown, 1827)		x	x			
Oenopota nobilis (Møller, 1842)		x				
Oenopota spp.		x	x			
Retusa obtusa (Montagu, 1803)		x	x			
Cylichna alba (Brown, 1827)			x			
Cylichna occulta (Mighels & Adams, 1841)		x	x			
Cylichna sp.		x	x			
Nucula nucleus (Linné, 1758)		x	x			
Nuculoma tenuis (Montagu, 1808)		x	x			
Nuculana pernula (Müller, 1779)				x		
Portlandia arctica (Gray, 1824)	x	x	x	x		x
Yoldiella fraterna Verrill & Bush, 1898		x	x			
Yoldiella intermedia (M. Sars, 1865)			x	x		
Bathyarca glacialis (Gray, 1824)		x	x			x
Mytilus edulis Linné, 1758			x			
Musculus niger (Gray, 1824)	x		x			
Arctinula greenlandica (Sowerby, 1842)	x			x		x
Astarte borealis (Schumacher, 1817)		x	x	x	x	x
Astarte elliptica (Brown, 1827)		x	x			
Astarte soror (Dall 1903)			x			
Astarte montagui (Dillwyn, 1817)	x	x			x	x
Arctica islandica (Linné, 1767)						x
Axinopsida orbiculata (G.O. Sars, 1878)			x			
Thyasira gouldi (Philippi, 1845)			x			
Montacuta dawsoni Jeffreys, 1863			x			
Serripes groenlandicus (Mohr, 1786)		x	x	x	x	
Clinocardium ciliatum (Fabricius, 1780)		x	x			
Macoma calcarea (Gmelin, 1790)		x	x			
Macoma balthica (Linné, 1758)		x	x			
Macoma moesta (Deshayes, 1855)						
Cyrtodaria kurriana Dunker, 1862		x	x	x	x	x
Hiatella arctica (Linné, 1767)		x	x	x	x	x
Mya truncata Linné, 1758			x	x	x	
Pandora glacialis Leach, 1819		x	x			
Cochlodesma sp.						

VERTEBRATES (Repenning et al. 1987, Fredskild & Røen 1982)

Gasterosteus aculeatus Linné			x			
Lepus sp.						
Hypolagus sp*.,						

Appendix 2

Strontium isotopes in molluscs from Kap København

Twenty-five bivalve shells from The Kap København Formation were analyzed for strontium isotopic composition (Table 2). The shells were first examined by X-ray diffraction (XRD) and only samples containing pure aragonite were used for isotopic analyses (detection level for calcite is about 1%). They were then cleaned in ultrapure water in an ultrasonic bath to avoid contamination from detrital material. Strontium isotopes were analyzed at the Danish Center for Isotope Geology following the procedure described by Israelson & Buchardt (1999). As a control, one recent sample (57512-1) taken offshore from Kap København was also analyzed and its $^{87}Sr/^{86}Sr$ ratio of 0.70918 is indistinguishable from present day seawater $^{87}Sr/^{86}Sr$. The fossil shells have $^{87}Sr/^{86}Sr$ ratios between 0.70911 and 0.71014.

The seawater $^{87}Sr/^{86}Sr$ ratio has increased since the Pliocene. Farrell et al. (1995) constructed a reference curve based on Sr isotope values of foraminifers from seven well-dated deep sea drill cores, which cover the time interval from 0 to 6 ma. The data fit a fifth-order polynomial equation that enables age determination of marine carbonate samples with known $^{87}Sr/^{86}Sr$ values. A lower than present day seawater isotopic ratio is therefore an age indicator, whereas a higher than present day $^{87}Sr/^{86}Sr$ ratio indicates that the molluscs lived in waters influenced by continental run-off (Israelson & Buchardt 1999). A less likely explanation for higher than present day $^{87}Sr/^{86}Sr$ ratios could be that the shells incorporated detrital particles in their shells that could not be removed by cleaning.

The lowest ratios measured in this study were 0.70911 (56862 and 57508, Table 2). An Sr isotope age for this value, 1.75 ma +1.6 -0.7 ma, can be calculated using the $^{87}Sr/^{86}Sr$ vs age equation with error limits of $\pm19 \times 10^{-6}$ from the fifth-order fit of the reference curve of Farrell et al. (1995), and $\pm15 \times 10^{-6}$ uncertainties on measured samples from this study. This very imprecise estimate must be considered a minimum age since some contamination by runoff water is probable, and in general agreement with other results. (The positive and negative uncertainties are not the same due to the non-linear nature of the Sr isotope reference curve).

Most samples have $^{87}Sr/^{86}Sr$ values higher than present day seawater, between 0.70922 and 0.71014. This probably indicates that the shells lived in brackish water, as suggested also by the benthic faunas. The strontium isotopic composition of brackish water is controlled by the Sr concentration and isotopic

composition of the fresh water component (Israelson & Buchardt 1999). Since nothing is known about the fossil drainage system, it is not possible to determine the salinity in which the bivalves lived. However, most river waters have much lower Sr concentrations than seawater and brackish water will normally be totally dominated by seawater Sr.

The list below shows $^{87}Sr/^{86}Sr$ ratios normalized to an NBS987 value of 0.710248. Precision on the strontium isotope ratios is $\pm15\times10^{-6}$

Locality	Member/unit	Species	$^{87}Sr/^{86}Sr$
33	allochthonous	*Arctica islandica*	0.70936
33	allochthonous	*Astarte borealis*	0.70923
51	allochthonous	*Astarte borealis*	0.70944
59	allochthonous	*Astarte borealis*	0.71014
59	allochthonous	*Astarte borealis*	0.70911
48	B1/B2	*Astarte sp.*	0.70944
48	B1/B2	*Astarte sp.*	0.70949
3	B2	*Cyrtodaria kurriana*	0.70924
68	B2	*Macoma balthica*	0.70929
72	B2	*Astarte borealis*	0.70911
72	B2	*Astarte borealis*	0.70913
72	B2	*Astarte borealis*	0.70948
75	B2	*Astarte borealis*	0.70914
128	B3	*Macoma balthica*	0.70966
128	B3	*Serripes groenlandicus*	0.70942
128	B3	*Astarte borealis*	0.7093
128	B3	*Astarte borealis*	0.70925
128	B3	*Astarte borealis*	0.70926
128	B3	*Astarte borealis*	0.70975
128	B3	*Astarte borealis*	0.70916
128	B3	*Astarte borealis*	0.70922
128	B3	*Astarte borealis*	0.70925
	Kap Rigsdagen	*Astarte borealis*	0.70927
	recent	*Astarte borealis*	0.70918