Holocene relative sea-level changes and deglaciation chronology in Finnmark, northern Norway

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Abstract

The outer coast of Finnmark in northern Norway is where the former Fennoscandian and Barents Sea ice sheets coalesced. This key area for isostatic modelling and deglaciation history of the ice sheets has abundant raised shorelines, but only a few existing radiocarbon dates relate to them. Here we present three Holocene sea-level curves based on radiocarbon ages from deposits in isolation basins at the outermost coast of Finnmark; located at the islands Sørøya and Rolvsøya and at the Nordkinn peninsula. We analysed animal and plant remains in the basin deposits to identify the transitions between marine and lacustrine sediments. Terrestrial plant fragments from these transitions were then radiocarbon dated. Radiocarbon-dated mollusk shells and marine macro-algae from the lowermost deposits in several basins suggest that the first land at the outer coast became ice free around 14.6 cal kyr BP. We find that the gradients of the shorelines are much lower than elsewhere along the Norwegian coast because of substantial uplift of the Barents Sea. After the Younger Dryas the coast emerged 1.6-1.0 cm per year until about 9500-9000 cal yr BP. Between 9000 and 7000 yr BP relative sea-level rose 2-4 m and several of the studied lakes became submerged. At the outermost locality Rolvsøya, relative sea level was stable at the transgression highstand for more than 3000 years, between ca. 8000 and 5000 cal yr BP. Deposits in five of the studied lakes were disturbed by the Storegga tsunami ca. 8100-8200 cal yr BP.

KEYWORDS: Relative sea level; shoreline; isolation basins; Finnmark; macrofossils; deglaciation; glacio-isostasy; Barents Sea Ice Sheet;

1. Introduction

The first written account of raised shorelines north of the arctic tree line in Finnmark was made by the French physicist Auguste Bravais, who participated in the French-Scandinavian *La Recherche* Expedition 1838–40 (Bravais 1842). He measured and documented that the ancient shorelines were not horizontal, but inclined landwards, an observation that eventually became an essential piece of evidence to the theory of glacial isostasy (Chambers 1850; De Geer 1888/1890; De Geer 1890). Since then the region has attracted a number of scientists, but unlike beach ridges in Svalbard (e.g. Bondevik et al. 1995) and Arctic Canada (e.g. Dyke 2004), the raised shorelines in Finnmark lack organic material, like driftwood logs, whalebones and shells, needed for radiocarbon measurements. Thus only a few radiocarbon dates related to the shorelines exist. Reconstructions of the shoreline displacement in the region have therefore been hampered by the lack of absolute age control.

To overcome the problem of not finding dateable material in the shorelines themselves, we have used the “isolation basin method” (Hafsten 1960) to reconstruct shoreline displacement at the outer coast of Finnmark (Fig. 1). We cored and investigated 18 lakes; eight of them hold deposits with clear signatures of sea level changes. Based on the acquired data we have constructed three Holocene sea-level curves. Our results deviate by up to several millennia from previously published sea-level reconstructions, which were based on regional correlations and relative chronology (Marthinussen 1960, 1962; Møller 1987, 1989).

Sea-level data from the outer coast of Finnmark can put constraints on the ice sheet configuration and deglaciation history in the area where the Fennoscandian Ice Sheet merged with the Barents Sea Ice Sheet (Fig. 1B). We find evidence that the uplift rates along the coast were influenced by rebound of the Barents Sea seafloor. Also very few of the ice-marginal deposits in Finnmark have been dated. Several of the investigated lake basins hold organic-rich, pre-Holocene sediments that were deposited in shallow-water marine environments. We present radiocarbon ages from these deposits and argue that the deepest dated samples provide close to minimum ages for the last deglaciation at the sites. The deposits in five lakes also contain traces left by the Storegga tsunami, which is presented in a parallel paper (Paper III: Romundset and Bondevik).

2. Regional setting

2.1. Area

The outer coast of Finnmark has a relatively mild and wet climate despite its high latitude (70-71°N). Warm ocean water flows northwards in the North Atlantic current and the coastal current, causing mild, snow-rich winters and cool, rainy summers. The mean annual air temperature is close to 2.0°C at sea level, with mean winter temperatures a few degrees below zero (DNMI 2010). The study area lies north of the arctic tree line, but patches of mountain birch (*Betula pubescens*) occur close to some of the localities. The study area is today rising about 1 ± 0.05 mm/yr relative to the sea level (Vestøl 2006), with uplift rates generally increasing towards the former Fennoscandian ice centre (Fig. 1A).

The landscape is characterised by undulating, barren mountain plateaux, where extensive autochthonous block fields reach down to about one hundred m a.s.l. (NGU 2010). Other Quaternary deposits in the area are scarce, and consist mainly of raised beach ridges, some terminal moraines and scattered patches of till (Sollid et al. 1973).

2.2. Deglacial history

The Fennoscandian Ice Sheet coalesced with the marine-based Barents Sea Ice Sheet to the north during the last glacial (Fig. 1B, e.g. Landvik et al. 1998; Mangerud 2004), and reached one or possibly two maxima around 22-19 cal yr BP (Vorren and Laberg 1996). Radiocarbon ages of mollusk shell fragments incorporated in tills and from post-deglaciation deposits above till have been used to reconstruct the approximate timing of glacial retreat in the Barents Sea area. These suggest that rapid retreat began along the western margin of the ice sheet at ca. 17 cal kyr BP (Winsborrow et al. 2010), and that the southern Barents Sea became deglaciated over ca. 2000 years and was ice free around 15 cal kyr BP (Polyak et al. 1995; Vorren and Laberg 1996; Landvik et al. 1998; Winsborrow et al. 2010).

Observations of discontinuous raised shoreline features and ice-marginal deposits in coastal Finnmark have been used to reconstruct seven deglacial ice-margin positions onshore (Marthinussen 1961; Sollid et al. 1973). Three of these are thought to represent significant halts or re-advances during the general recession (Fig. 1A; Sollid et al. 1973), but their ages are poorly constrained. Correlations have been made to observations mainly from Lofoten and Vesterålen (Fig. 1B) farther west, using Tanners (1930) so-called ‘shoreline relation method', that presupposes proportionality between systems of raised shorelines from different regions (Marthinussen 1960; Møller and Sollid 1972; Olsen et al. 1996; Ottesen et al. 2008). According to this, the outermost coast of Finnmark became ice free around 18 cal kyr BP, the Outer Porsanger sub-stage dates to 17 cal kyr BP and the Repparfjord sub-stage dates to ca. 14 cal kyr BP. However, a younger age of 15 cal kyr BP has been suggested both for the first ice-free land (Landvik et al. 1998), and for the Outer Porsanger sub-stage (Winsborrow et al. 2010). The chronology of glacial retreat in Finnmark is discussed in this paper, in the light of new radiocarbon dates from isolation basins.

2.3. Shoreline displacement

In the earliest description of raised shorelines in Finnmark (Bravais 1842), two tilted levels were pointed out as morphologically distinct; the 'Main' and the 'Tapes' shorelines. These two shorelines are continuous over long distances along the fjords in Finnmark, and can also be correlated along the entire west coast of Norway (Sørensen et al. 1987). The Main shoreline is in most areas an erosional feature and is thought to have been formed during the Younger Dryas, with relatively stable sea level, long lasting sea-ice cover and active frost-shattering processes (Andersen 1968; Blikra and Longva 1995). The Tapes shoreline on the other hand, is represented mainly by large beach ridges that accumulated at the peak of the mid-Holocene transgression.

In addition to these two pronounced levels, traces of former shorelines are found at many other altitudes between the marine limit and the present sea level. Based on detailed investigations in eastern Finnmark through several decades, Tanner (1930) published a classification system where he distinguished 13 pre-Holocene and 11 Holocene shorelines. He found diachronous Tapes transgression features that led him to conclude that the transgression occurred fourfold; i.e. that relative sea level oscillated repeatedly through large parts of the Holocene. His systematic shoreline classification has had a large influence on other studies in northern Norway until today, although no such fluctuations have been demonstrated in comprehensive isolation basin studies covering the Tapes transgression period elsewhere in Scandinavia (e.g. Svendsen and Mangerud 1987; Corner and Haugane 1993).

Tanners work was followed up by several investigators, most notably Marthinussen (1960), who identified altogether 40 different raised shorelines in western Finnmark; 18 above the

Main shoreline, 12 between the Main and Tapes shorelines and 9 below the Tapes shoreline. The landward extension of the pre-Holocene shorelines were later used to reconstruct halts in the ice recession (Sollid et al. 1973), and many studies have used the shoreline diagrams for dating purposes, despite the lack of chronological constraints (e.g. Corner 1980; Hald and Vorren 1983; Corner and Haugane 1993; Fletcher et al. 1993; Bakke et al. 2005).

Only a few radiocarbon dates relate to past sea levels in western Finnmark; these are of driftwood found close to Tapes levels (Marthinussen 1962). Neither shells nor pumice occur at the surface above the Tapes shoreline in Finnmark (Tanner 1907; Hansen 1918; Marthinussen 1945; Donner et al. 1977). Farther east, shell samples from raised beaches, peat below beach gravel, charcoal at archaeological sites and lake isolations have been dated along the Varanger peninsula and towards the Russian border (Fig. 1A, Marthinussen 1962; Donner et al. 1977; Helskog 1978; Corner et al. 1999).

Interpretation of these chronological data has been challenging and has resulted in conflicting reconstructions. The problems arise due to difficulties with correctly relating the various findings to past sea level, since beach ridges are both discontinuous and non-uniform. The size, shape and overall existence of raised beach deposits along the coast of Finnmark depend mainly on the local topographic setting and nearby availability of surficial deposits (Sanjaume and Tolgensbakk 2009). The geographically nearest sea-level reconstructions that rely on radiocarbon-dated isolation basin sequences are situated about 200 km to the east and 150 km to the west of our localities (Corner and Haugane 1993; Corner et al. 1999).

In an attempt to combine all available observations, Møller (1987; 1989) made a computer-based geometrical simulation where sea-level curves could be generated for any chosen locality in northern Norway, based on the ‘shoreline relation’ principle. The computer software has since been widely used for educational purposes and by archaeologists working in the region.

3. Methods

3.1. Field work

Long stretches of the Norwegian coastline are characterized by a low-lying, undulating strandflat (Nansen 1922), where lakes and bogs are common, but in Finnmark steep sea cliffs border the Barents Sea and only few lakes exist below the marine limit (Sollid et al. 1973; Corner 2005). We searched for places at the outer coast with several closely spaced lake basins at altitudes below the Main shoreline, using aerial photographs and maps with scale down to 1:5,000. Three suitable areas were found; Sørøya, Rolvsøya and the Nordkinn peninsula (Fig. 1A). We started at Sørøya using a snowmobile to transport the coring equipment to the sites, but found that this was very difficult due to little snow cover close to sea level. The lakes at Rolvsøya and Nordkinn are located relatively close to roads and equipment and core samples could here be man-hauled using a sledge.

Basin thresholds at Rolvsøya and Nordkinn were examined and levelled in the autumn of 2009 and all were found to consist of bedrock; there are no signs of fluvial incision or peat accumulation at the thresholds. The altitudes of the lowermost points at the basin thresholds were levelled to the nearest benchmark (NMA 2002). The benchmark system refers to datum level NN1954, which in Hammerfest lies 10 cm and in Honningsvåg 13.4 cm above mean sea level (Fig. 1A, NHS 2010; O. Vestøl, Norwegian Mapping Authority, pers. comm. 2009). The determined values were accordingly corrected to represent elevations above mean sea level. Benchmark elevations are given with uncertainties ± 5 and ± 3 cm (NMA 2002) and we conservatively use ± 10 cm precision for the levelling based on the deviation values we found after repeated measurements. Basin elevations are given in this paper with the sum of the uncertainties.

The basins at Sørøya have only been studied in winter; their elevations were therefore acquired from 1:5,000 maps. Based on our experience from levelling at the other localities, we assume that the basins at Sørøya lie within 1 m of the map elevations. Both of the basins at Sørøya used for the sea-level reconstruction are dammed by blocky moraine where we assume minimal incision since isolation.

Coring took place in late spring 2007 and 2008 from solid lake ice and at air temperatures around 0°C. Lake bathymetry was mapped along several transects across each basin prior to coring. The coring equipment was traditional ‘Russian type’ peat corers of various cylinder diameters (Jowsey 1966) and a ‘Nesje type’ piston corer (Nesje 1992). The deposits in the shallow lakes were mapped laterally with a Russian peat corer, but in some cases the lakes were too deep (> ca. 8 m) and only the piston corer could be used.

3.2. Laboratory work

Magnetic susceptibility of the cores was measured to document changes in the content of minerogenic material. The magnetic susceptibility (MS) values of marine sediments are generally higher than those of lacustrine sediments, a difference especially pronounced in early Holocene isolation sequences. Loss-on-ignition (LOI) analysis was performed through sequences of particular interest, to further document changes in organic content. All stratigraphies were carefully described, photographed and logged, and many levels were X-ray photographed. In this paper, all depths are given below the lake surface.

We analysed the plant and animal macrofossils in the basin deposits to determine the changes between marine and lacustrine environments in the basins. Many of the remains we find in the deposits come from organisms that are unique to marine or limnic environments. Usually, diatoms are used to reconstruct environmental changes from isolation basin deposits (e.g. Hafsten 1960; Kjemperud 1981; Lohne et al. 2004) and are often thought to be superior to other methods to record salinity changes of the surface water. However, plant and animal macrofossils have also been used along with or instead of diatoms in sea-level studies in Greenland (Björck et al. 1994a, 1994b; Bennike 1995; Bennike et al. 2002; Sparrenbom et al. 2006a, 2006b; Wagner et al. 2010), in Canada (Miousse et al. 2003) and in central Norway (Solem et al. 1997; Solem and Solem 1997). A practical advantage of analysing macrofossils is that terrestrial material for radiocarbon dating can be picked out and identified at the same time.

Sediment samples of ca. 10 cm^3 were cut from 1 cm thick segments of the core, wet sieved on 250 and 150 µm mesh widths, and the residue was investigated under a stereomicroscope. All remains larger than 150 µm were identified to various taxonomic levels and classified as macrofossils, although tests from foraminifers and testate amoebae by definition are microfossils. The relative frequencies of the different species were evaluated, and are reported as ‘none’, ‘present’ or ‘common’. Animal and plant remains found useful for the isolation basin analyses are listed in Table 1, and photographs of selected types are shown in Figure 2. In Table 1 the occurrence of these fossils in other isolation basin studies is also given. The biostratigraphy is described for each lake in section 4, along with details for each species. A further evaluation of our experience with the method is included in the discussion.

3.3. *AMS ^{14}C-dates*

All radiocarbon dates used for the sea-level reconstruction have been obtained on identified remains of terrestrial plant macrofossils, using accelerator mass spectrometry (AMS) dating. The ages have been calibrated with the computer software OxCal v4.1 (Bronk Ramsey 2009) using the Intcal09 dataset (Reimer et al. 2009) and all calibrated ages are given with two standard deviations (Table 2) and cited in this paper as "yr BP". Radiocarbon ages of marine samples were calibrated using the Marine09 dataset (Reimer et al. 2009) with a reservoir age of 437 ± 18 years and a ΔR-value of 71 ± 21 years. This value is the pooled mean of 5 samples from northern Norway and the Barents Sea (Mangerud et al. 2006) and is currently the best reservoir-age estimate for seawater at the coast of Finnmark.

4. Results

4.1. *Rolvsøya*

We investigated four closely spaced lakes located in Tufjord at Rolvsøya between 5 and 12.5 m a.s.l. (Fig. 3A, B; 70°59.8'N 23°56.3'E). Three of the basins contain deposits that document sea-level changes. These lakes were also inundated by the Storegga tsunami (Paper III: Romundset and Bondevik). All three lakes have clearly defined bedrock thresholds that were levelled from a triangulation point some 200–500 m NE of the lake outlets. We did not recover any deposits from the highest lake at 12.5 m a.s.l., which is small and shallow.

4.1.1. Basins, deposits and radiocarbon ages

Lake 5: Storvatnet 5.27 ± 0.11 m a.s.l.

Storvatnet (Fig. 3B) is a large (700 x 200 m), mostly 2-4 m deep lake with a relatively flat bottom. The lake remained below sea level from deglaciation until ca. 11,000 yr BP when it was isolated, but became submerged again between ca. 8000-5000 yr BP during the Tapes transgression. Massive erosion by the Storegga tsunami removed the earliest isolation boundary at all core sites except for the innermost one, core 5R-6 (Fig. 3D).

The basin was first isolated from the sea at 11,180-10,770 yr BP. Deposits below 470 cm in core 5R-6 (Fig. 3D) contain remains of marine brown algae (phaeophyceae) and skeleton fragments of Hydroidea (Figs. 2 & 5C, Table 1). Among the brown algae, two species were identified to *Sphacelaria* and *Desmarestia aculeata* (Table 1), the latter recognised from its spiked stems (Jaasund 1965). Both species grow mainly at sublittoral depths both in exposed and sheltered locations (Jaasund 1965; Rueness 1998). The sample at 467 cm contained no marine organisms but a few remains of limnic organisms. From here, loss of ignition rises abruptly from ca. 5 to 20 % (Fig. 3C). At 460 cm depth there are huge quantities of many macrofossils indicative of fully freshwater conditions, e.g. the bryozoans *Plumatella repens* and *Fredericella indica* (Fig. 2, 5C, Table 1). Bryozoans are colonial animals, and some of the freshwater species produce durable statoblasts of chitin. They mainly live down to 2 m depth in standing or slowly flowing water, and occur in lakes all over Norway from sea level to above the tree line (Økland and Økland 2005). Both *Plumatella repens* and a third species, *Cristatella mucedo* (Fig. 2, Table 1), are common in our lake records, whereas *Fredericella indica* is less common; it is apparently new to the fossil fauna of Norway although it is common today in northern Norway (Økland and Økland 2005). *C. mucedo* occurs here at its northernmost distribution, which follows approximately the 10°C mean July isotherm (Birks 2000; Økland and Økland 2005). The isolation boundary is thus placed at 467 cm and leaves of mainly Salix herbacea from 466-465 cm were radiocarbon dated to 11,180-10,770 yr BP (Table 2).

Piston core 5-1 did not penetrate the tsunami deposits, but it has been used to study later sea-level changes (Fig. 3C). The sediments from the bottom of the core at 936 cm up to 919.5 cm consist of laminated gyttja, with alternating black and olive-green laminae (photograph b in Fig 3E). Loss on ignition is ca. 28 % at the bottom but drops to below 20 % above the laminae (Fig. 3C). The macrofossils in this segment are, except for a few Hydroidea, purely of limnic origin (Fig. 5B). Marine algae appear at 915 cm and from 910 cm large numbers of different foraminifera and other remains of marine organisms dominate. We place the ingression boundary at 920-919 cm in this core and radiocarbon dated *Empetrum nigrum* leaves from this depth to 8020-7850 yr BP and an unidentified twig with bark to 7680-7520 yr BP (Table 2). It seems more likely that the younger twig sunk into the sediments than that the delicate leaves were re-deposited for several hundred years; we therefore put most confidence in the older age. The dated level represents the time when the basin no longer contained anoxic water, which during an ingression might be slightly later than the actual time when highest astronomical tide passed the lake threshold. However, the age of the tsunami deposit below makes it only possible that it is ca. 100 years older, and this has been taken into account in our analysis.

The sediments between 920-680 cm were deposited when the lake was submerged and consist of organic-rich, shell-bearing mud that becomes indistinctly layered above 800 cm and is laminated from 735 cm. The laminae become thinner upwards and ends in a zone of thin, alternating black and brownish-greyish laminae between 700 and 680 cm (photograph a in Fig. 3E). Loss on ignition also rises through the laminated part, but is generally high (20-30%) throughout the core. Brown gyttja is found above 680 cm and up to the lake floor.

Marine macrofossils dominate up through the banded and laminated sediments, and disappear at 680 cm (Fig. 5A). Above that level limnic species again prevail, e.g. ephippia (resting egg pouches) from the crustacean *Daphnia pulex* (water flea, Table 1), bryozoans and Trichoptera (caddis fly, Table 1) larvae tubes. Trichoptera larvae are aquatic and many species build protective tubes, which are often well preserved in sediments and indicate a freshwater origin. The tubes look somewhat similar to tubes from the marine polychaete worm *Pectinaria* (Table 1), but the larvae tubes of caddis flies are generally much smaller and appear more coloured whereas the worm tubes usually are greyish. Vegetative remains from the aquatic plant *Myriophyllum* (water milfoil, Table 1) were also found at this level, as well as in some of the other studied basins. It grows submerged and the remains are common in lake sediments but have not previously been reported from isolation boundaries, although pollen from the plant is commonly found in early Holocene basin isolation sequences in western Norway (Kaland 1984a). A sample of mostly *Empetrum nigrum* leaves from 681-680 cm was radiocarbon dated to 5300-4960 yr BP (Table 2) and reveals that Storvatnet again became isolated at after more than 3000 years of inundation during the Tapes transgression.

Lake 6: Lillerundvatnet 5.83 ± 0.11 m a.s.l.

Lillerundvatnet (Fig. 3B) lies just next to Storvatnet, and only about 60 cm higher. A ca. 10 m long stream connects the two lakes today. The lake is small (180 x 150 m), only about 1 m deep and partly overgrown. The piston core 6-1 (Fig. 4) recovered an almost 6 m long sequence, dating back to the Bølling chronozone.

The lower 1.5 m of the core contains Lateglacial silty sand with shells and layers of seaweed. The latter give rise to high loss on ignition (LOI) values (up to 20 %) and fluctuating magnetic susceptibility values. Similar seaweed layers occur in Late Weichselian shallow marine sediments from raised lakes in Vesterålen (Fig. 1; T. Vorren et al. 1988). A half of a *Mya truncata* shell found at 649 cm was radiocarbon dated to 14,790–13,860 yr BP (Table 2); this gives a minimum age for ice-free conditions at Rolvsøya. Between 620-590 cm the deposits contain more pebbles than below and above (Fig. 4) and are at the same time devoid of mollusk shells or other organic material (LOI is 0%). More fine-grained and homogenous silt dominates above that level. The age of marine algae at 528 cm depth is 12,750–12,540 yr BP (Table 2), implying that the light grey silt above, with LOI of 0 % and laminated between 515 and 480 cm, was deposited during the Younger Dryas. A rock (diameter 10 cm) that possibly became rotated during coring is situated at 475–464 cm. The rock is enclosed by slightly organic silt (ca. 5% LOI), increasingly brownish upwards.

A few distinct laminae are found at 449-448 cm and LOI increases rapidly across the level from ca. 8 to more than 20 %. Hydroidea is common at 455 cm, but above that level both Hydroidea and marine algae disappear and at 445 cm there is a sudden rise in Tricoptera larvae tubes, the bryozoans *Plumatella repens* and *Cristatella mucedo*, and oogonia from the charophytes (green algae) *Nitella* and *Chara* (Fig. 5D, Table 1). These charophytes are mainly limnic, but some species of both genera grow in brackish water. *Nitella* oogonia are much more frequent in our material than the more thermophilous *Chara,* like in Lateglacial deposits from western Norway (Birks and van Dinter 2010) and in most of Greenland (Bennike 2000). The opposite distribution was found in mid-Holocene sequences from central Norway (Solem and Solem 1997). Numerous head capsules from the fresh water larvae of Chironomidae (non-biting midge) appear at 445 cm (Fig. 5D). A distinct increase in the amount of insect remains is characteristic for isolation boundaries, and Chironomidae larvae head capsules are by far the most common.

The isolation boundary has been dated at 448–449 cm to 11,390–11,170 yr BP, using *Salix herbacea* and Ericaceae leaves (Table 2). *Drepanocladus* stems (aquatic moss) picked from the same sediment sample were dated to 11,610–10,900 yr BP, i.e. the same age. This result suggests that *Drepanocladus* is free from hard-water problems as long as there is no carbonate bedrock in the catchment area. Interestingly, the occurrence of *Cristatella mucedo* at the dated isolation level is ca. 500 years older (using the weighted mean age) than the colonisation age reported from Andøya farther west (K.-D. Vorren et al. 2009). The coast of Finnmark is presently the northern distribution limit of *C. Mucedo* (Birks 2000), this thus documents that the mean summer temperature at the time of isolation had become comparable to the present.

The sediments above the isolation boundary are dominated by limnic macrofossils, but a significant amount of marine species occur between 415 cm and 370 cm depth (Fig. 5D). The sediment is also vaguely banded between ca. 400-290 cm. We think this segment with a mixed, but predominantly limnic, macrofossil assemblage was deposited when astronomical high-tide sea level stood close to the threshold elevation of the basin during the highstand of the Tapes transgression. The inclusions of marine species might be due to transport by sea spray or wave-wash and/or storm-surge tides above highest astronomical tide level.

Lake 7: Badevatnet 7.95 ± 0.11 m a.s.l.

Badevatnet (Fig. 3B) is a large (620 x 170 m), oblong and shallow lake, similar to Storvatnet. The gyttja in this lake has unusually high minerogenic content and is therefore extremely compact. Penetration was only successful with the piston corer, and we retrieved the ca. 3 m long core 7-1. The sediments comprise brown lacustrine gyttja, interrupted by Storegga tsunami deposits in the middle of the sequence (Paper III: Romundset and Bondevik).

A dating of terrestrial plant remains from the bottom of the core, at 487 cm depth, yielded 9260–8780 yr BP (Table 2). From the recovered sequence it is possible that the lake was below sea level in the early Holocene, yet we find it unlikely considering the isolation ages of the lower basins and the reconstructed Main shoreline at 6 m a.s.l. (Marthinussen 1960). The macrofossil record from Badevatnet shows no signs of marine influence during the mid-Holocene, except for the Storegga tsunami sediments, consistent with observations from the two other investigated records from Rolvsøya.

4.1.2. Holocene relative sea-level curve for Rolvsøya

The two earliest basin isolations document that relative sea level fell from the Main shoreline in the beginning of the Holocene. Storvatnet became submerged during the Tapes transgression, but the sea level did not rise above Lillerundvatnet. Storvatnet became isolated again ca. 3000 years later and the curve is drawn accordingly with a long-lasting standstill at the transgression highstand (Fig. 10A).

The level to which the sea fell prior to transgression is unknown, but according to Marthinussen (1960) it should have reached 1-2 m below present sea level. We do not believe it reached as low, considering our results from Nordkinn. The development during the Tapes transgression is now well constrained and shows that sea-level reached 5.2-5.9 m a.s.l. around 8000 yr BP where it remained stable for about 3000 years. This deviates from Marthinussens (1960) reconstruction which places the transgression maximum at ca. 9 m a.s.l. According to Møller (1987), the Tapes shoreline in Tufjord should be found at about 3 m a.s.l. These estimates were found by regional shoreline correlation and are not based on field observations at Rolvsøya, and it is apparent from our new results that the old shoreline reconstructions are largely erroneous for the mid-Holocene at Rolvsøya.

The standstill at the transgression highstand is in conflict with a suggested rapid eustatic sea-level rise of up to 9 m at 7.6 ± 0.1 kyr BP (Blanchon and Shaw 1995; Yu et al. 2007). Such an event, even of much smaller magnitude, would by far have exceeded the isostatic rebound and shown up in the Rolvsøya records.

4.2. Sørøya

We cored four lakes on Sørøya situated below the marine limit (Fig. 6A). Two of the lakes show significant changes between marine and lacustrine sediments and are further presented below. However, we did not recover marine sediments from Nedre Høyvikvatnet (28.5-29.5 m a.s.l.) and Øvre Høyvikvatnet (34-35 m a.s.l.). Both lakes have several metres long records of Holocene gyttja, with ca. 1 m of organic-poor silt below. We found only limnic macrofossils in these deposits. A distinct *Betula* pollen rise was identified in the lower part of the gyttja in Øvre Høyvikvatnet and dated to 10,490–10,230 yr BP (Table 2; K.-D. Vorren pers. comm. 2009).

4.2.1. Basins, deposits and radiocarbon ages

Lake 4: Lillevatnet 10.5-11.5 m a.s.l.
Lillevatnet is a small lake (Fig. 6A, 150 x 75 m, 70°37.0'N 22°42.9'E) that occupies a 3–4 m deep depression in till at the head of a fjord. We found clear indications that the Storegga tsunami flowed into the lake (Paper III: Romundset and Bondevik) and caused erosion and re-deposition. Later the lake was submerged for about 1600 years during the Tapes transgression, from about 8000 to 6600 yr BP.

Only core 4R-2 (Fig. 6A) penetrated the Storegga tsunami sand, dated on an Ericaceae twig found just above the deposit to 8310-8020 yr BP. The tsunami deposit rests on marine silt, and terrestrial plant remains found in the silt just below the erosional unconformity, were radiocarbon dated to 11,070-10,250 yr BP (Table 2). This shows that sea level stood above the threshold (deposition of marine sediments) at this time and also that the tsunami eroded away about 2000 years of deposition at the core site.

Blackish, laminated gyttja between 512-507 cm in core 4-5 occurs on top of Storegga tsunami deposits (Fig. 6B) and has a mixed assemblage of remains from marine and lacustrine organisms (Fig. 7B). A *Juniper* twig at 506-507 was dated to 8170-7970 yr BP (Table 2). The same laminated deposit in core 4-3 is thicker (37 cm) and was also analysed (Fig. 7C) to substantiate our interpretation of an ingression. According to the macrofossils in core 4-3, however, the ingression boundary should be placed somewhat lower than the top of the laminae (Fig. 7C). The dated level from core 4-5 is thus probably situated slightly higher than the boundary but it still gives a representative age, as judged from the ca. 8100 years old tsunami deposits found below.

At 505 cm the laminae disappear, the sediments change to olive-grey mud, loss on ignition decreases from about 500 cm (Fig. 6B), and the number of marine organisms increases up-core (Fig. 7B). Among the macrofossils are numerous vertebrae from *Mallotus villosus* (capelin, Fig. 7B, Table 1), both at 495 and 485 cm. The vertebra is readily recognisable due to the large hole that runs through the centre of it. Marine fossils dominate up to 455 cm (Fig. 7B).

Blackish, laminated gyttja appear again between 465 and 453 cm (Fig. 6B), representing the final isolation of the lake. The macrofossils show a marked change from a large number of various marine species to solely limnic species at 450 cm (Fig. 7B). Fruits of *Ruppia* (ditch grass; Fig. 2, Table 1) were found at 455 cm. *Ruppia* is a vascular plant with high salinity tolerance; it grows submerged in brackish or saline waters. At 450 cm we found white coloured megaspores from the lacustrine plant *Isoëtes* (quillwort, Table 1). It grows on the lake bottom with penetrating roots that commonly contaminate bulk-dating samples from isolation boundaries (Kaland et al. 1984b). According to the macrofossils the isolation boundary is somewhere between 455 and 450 cm, and a *Betula* twig from the top of the laminated part at 453 cm was radiocarbon dated to 6610-6400 yr BP (Table 2).

Lake 3: Tomasvatnet 16.5-17.5 m a.s.l

Tomasvatnet (Fig. 6A) is a large, oblong lake (750 x 130 m, 70°33.8’N 22°37.9’E), dammed by a terminal moraine in the lower reach of a narrow valley. The deposits in the lake comprise marine silt in the lower part and lacustrine gyttja above. Most of the lake is only a few metres deep, with a deeper trough down to about 12 m in the middle part. We collected four Russian cores from the shallow areas and the piston core 3-4 from the trough; the latter held the only continuous sequence (Fig. 6C), and has been subject to further investigations.

The core stopped at 1375 cm in brownish, slightly organic silt. Loss on ignition is 5-8 % at this level and decreases to 0 % from about 1330 cm. The colour and slightly higher LOI values of the lowermost segment would suggest that it was deposited during the Allerød, but the silt does not contain mollusk shells or enough terrestrial plant macrofossils for radiocarbon dating. The deposit is light grey and massive from 1330-1257 cm. At 1256 cm there is a distinct, black 2-3 mm thick layer followed by a few thinner, vague laminae (photograph a in Fig. 6C). At the black layer the macrofossil assemblage changes abruptly from marine to limnic (Fig. 7A) and a sample of *Drepanocladus* (aquatic moss) picked from 1255-1257 cm has a radiocarbon date of 11,250-11,810 yr BP (Table 2). A rise in organic content is recorded somewhat higher, around 1235 cm where a sample of *Carex* seeds and *Betula* leaves yielded 9890-9540 yr BP (Table 2).

Calcareous tests of the benthic foraminifer *Elphidium excavatum* are common at 1257 cm (Fig. 7A). This species along with the agglutinated *Eggerelloides scabrus* (Fig. 2, Table 1) are the two most frequent foraminifera in the records from Finnmark. Both species tolerate low salinities and are common at shallow depths in south-western Norway today (Austin and Sejrup 1994). A Cephalopoda (squid) beak was also found at 1257 cm depth (Fig. 7A, Table 1). Fossil squid beaks have previously been discovered only twice in Greenland (Bennike, unpubl. data) but are common in fossil penguin droppings in Antarctica (e.g. Emslie et al. 1998). At 1254 cm several limnic species occur suddenly in large numbers, e.g. Trichoptera, *Fredericella indica* and *Daphnia pulex* (Fig. 7A).

4.2.2. Holocene relative sea-level curve for Sørøya

The stratigraphy and radiocarbon ages described above constrain the relative sea-level changes to rapid regression in the period around 11,500-10,500 yr BP, with a gradually decreasing rate before transgression between 9000-7000 yr BP (Fig. 10). Since then, relative sea level has fallen to the present shoreline. According to the shoreline diagram of Marthinussen (1960), the relative sea level low stand should be around 7-8 m, which could fit with our dates but we have drawn the sea-level curve slightly higher in accordance with our findings at Nordkinn, described below. The level of the transgression high-stand is probably around 11 m a.s.l. and a ‘distinct shore line’ at 11.2-11.7 m a.s.l. (Marthinussen 1960) is assumed to represent the Tapes transgression maximum. Radiocarbon ages of two *Picea* driftwood logs found at 10.5–11.0 m a.s.l. near the base of a mire close to Lillevatnet, are reported at 5500 ± 150 and 5700 ± 150 ^{14}C yr BP (Marthinussen 1962). This corresponds to

6000–7000 cal yr BP (Fig. 10) and implies that the logs stranded during the maximum Tapes transgression.

4.3. Nordkinn

The Nordkinn peninsula is presently connected to the mainland by the 1–2 m high isthmus *Nuorri* (Fig. 8A), the name of which literally means ‘strait’, and thus testifies to a lower land level in the recent past. We cored eight lake basins in the western part of the peninsula (Fig. 8A). The basin sills were levelled over 900–1500 m beeline distances from two different national network benchmarks.

Four of the basins have been used for sea-level reconstruction and are described in detail below. The remaining lakes were not found suitable for sea-level studies. Øvre Snappvikvatnet at 34 m a.s.l. is large and deep, with a hard bottom and almost no organic sediments. A lake at 9 m a.s.l. near Kifjorden contains only a little gyttja on bedrock. Nedrevatnet and Storvatnet near the head of Oksefjorden (Fig. 8A) are situated at about 3 and 4 m a.s.l., respectively. The former is not fully isolated yet; it holds solely marine/brackish sediments in a long core. Storvatnet does have an isolation boundary in the uppermost part of a long sequence, where marine species disappear and a number of freshwater taxa such as *Gasterosteus aculeatus* (stickleback, Table 1), *Lepidurus*, Rhabdocoela, Trichoptera and *Isoëtes* appear. Two samples of terrestrial plant remains from the isolation boundary were submitted for dating, but high sulphur content of the material made radiocarbon measurements impossible.

4.3.1. Basins, deposits and radiocarbon ages

Lake 14: Kifjordvatnet 10.61 ± 0.10 m a.s.l.

This large, mostly < 2 m deep lake (Fig. 8A; 670 x 180 m, 70°55.5’N 27°26.2’E) is important to our reconstruction of the regression minimum in Finnmark. The oldest recovered sediments are dated to ca. 11,000 yr BP, prior to the isolations of nearby lakes at higher elevations, and marine sediments were likely deposited continuously until isolation that has been dated to 5470-5050 yr BP. From this we infer that the sea did not reach lower than this level prior to the transgression, and that sea level is thus constrained within at most 2.7 m for more than 4000 years in the mid-Holocene (Fig. 10C). However, we have only one core from the lake and although we find it unlikely, we cannot rule out the possibility that sea-level dropped below the lake and that later erosion removed lacustrine sediments and left a hiatus in the record.

The piston core stopped in sediments containing clasts at 517 cm depth (Fig. 8B), probably near the boundary to the Younger Dryas. Fragments of *Desmarestia aculeata* (brown algae) picked from 517-512 cm were radiocarbon dated to 11,230-10,900 and a similar sample from 512-507 cm yielded an age of 11,040-10,600 yr BP (Table 2). A much younger age of shell fragments that must have been brought down by the piston corer was rejected (Table 2). Between 470–351 cm the core holds a mixture of coralline algae fragments interspersed with silt and mollusk shell fragments (Fig. 8B, photograph a in Fig. 8F). This segment was deposited during a period when the basin was an unsheltered bay, with the coring site situated well above wave base. Sedimentation of marine mud commenced as the basin approached isolation.

At 352-351 cm there is a sharp transition from the coralline algae gravel below to organic mud above. From here LOI rises from 10 % to 40 %, and the deposit between 338-336 cm is blackish, laminated gyttja (photograph a in Fig. 8F). From the macrofossils we place the isolation boundary here, but material from a longer interval than usual (344-333 cm) was needed to get enough plant material for radiocarbon dating. An age of 5470-5050 yr BP was obtained (Table 2), and we also dated fragments of *Desmarestia aculeata* from the same interval which gave a reservoir corrected age of 5280-4960 yr BP.

The macrofossils across the isolation boundary show a typical development. Hydroidea, *Pectinaria* and marine brown algae were found at 342 cm (Fig. 9A). *Pectinaria* (Table 1) is a polychaete worm that builds conical tubes from sand grains, cemented by a grey substance that makes them appear greyish. Only few macrofossils are present in the laminated part, but an increase of Chironomidae is seen at 337 cm. A change to lacustrine environment is documented from numerous limnic organisms at 332 cm: *Nitella*, *Daphnia pulex*, *Cristatella mucedo*, exoskeletons from Oribatida (Fig. 2, Table 1) and tests from testate amoebae. Two forms of testate amoebae (Fig. 2, Table 1), one with globe-shaped tests identified as ?*Centropyxis*, the other with pear-shaped tests identified as *Difflugia pyriformis,* have been found. Oribatida are commonly named soil mites, but some species are limnic and become preserved in lake sediments. The rest of the core, from 336–237 cm, comprises brown homogenous gyttja.

Lake 15: Kifjorddammen 13.10 ± 0.10 m a.s.l.

The shallow and small Kifjorddammen (Fig. 8A, 80 x 60 m, 70°55.4'N 27°25.6'E) was isolated in the early Holocene and subsequently became inundated by the Storegga tsunami (Paper III: Romundset and Bondevik). One piston core was taken from the middle of the lake.

The core reached into Lateglacial deposits. From the bottom of this core, between 389-380 cm depth we dated a large fragment of *Chlamys islandica* to 13,810-13,460 yr BP. Further up-core, a half of a *Mya truncata* shell at 342 cm yielded 13,470–13,200 yr BP (Table 2). These marine shells were found in a light-grey deposit of silt with pebbles and shells probably deposited distal to a glacial meltwater source. Pebbles and shells disappear and massive clayey silt is present between 331-302 cm. An erosional unconformity was discovered at 302 cm depth (Fig. 8C), followed by ca. 10 cm of unsorted sandy silt, with pebbles and marine algae remains. Marine algae found in homogenous silt at 293 cm just above the deposit were dated to 11,080-10,620 yr BP (Table 2), thus providing an age for the unconformity.

Grey, organic-poor silt continues from 292-274 cm and at 280 cm we found byssus from *Mytilus edulis* (blue mussel, Fig. 9B). Mollusk shells are common in shallow-marine sediments, but most often they disappear well before a basin becomes isolated. However, *M. edulis* tolerates low salinities and their byssus filaments (attachment threads; Fig. 2, Table 1) are resistant to degradation. The silt changes colour from grey to darker brownish-grey, becomes increasingly organic and laminated at 274–269 cm (photograph b and X-ray radiograph c in Fig. 8F). Limnic species appear at 272 cm (Fig. 9B); particularly abundant are hard fruits from the aquatic plant *Potamogeton* (pondweed, Table 1).

The isolation boundary is placed at this level. Terrestrial plant remains from 273-270 cm were radiocarbon dated to 9910-9540 yr BP, and a large sample of *Potamogeton* fruits from the same level yielded 10,720–10,300 yr BP (Table 2, Fig. 8C). The offset of 840 years (using weighted average ages) between the samples is probably caused by hard water effect, since potentially carbon-bearing metasedimentary rocks are found in the watershed (NGU 2010). Aquatic moss from just above the isolation boundary also yielded a slightly older age than the terrestrial plants (Table 2, Fig. 8C).

Sediments we think were deposited by the Storegga tsunami occur between 261–211 cm (photograph b and X-ray radiograph c in Fig. 8F). Some pebbles (diameter up to 3-4 cm) occur in the lower part above the erosional unconformity, followed by re-deposited marine silt (identified by macrofossil species), gyttja and coarse organic remains. A twig that probably was washed from the watershed and re-deposited into the lake by the tsunami was found at 254 cm and radiocarbon dated to 8580-8390 yr BP. Ca. 1500 years worth of sedimentation were removed by the tsunami at the core site. Brown gyttja was found above the tsunami deposit and continues to the lake floor at around 90 cm depth.

Lake 10: Nedre Snappvikvatnet 18.18 ± 0.10 m a.s.l.

Nedre Snappvikvatnet (70°56.6'N 27°17.9'E) is a small lake (290 x 70 m) that was isolated from the sea in the early Holocene (Fig. 8A, 8B). From the bottom of core 10-1 at 650 cm dark grey silt with scattered marine algae is found up to 560 cm (Fig. 8D). A sample at 580 cm contained remains from several marine species like *Elphidium excavatum*, *Pectinaria* and *Mytilus edulis* (Fig. 9C). The colour changes around 566–565 cm from grey to olive-brown (photograph e in Fig. 8F), and across the same level loss on ignition rises from 2-3 % to >30 % and the magnetic susceptibility decreases. Large numbers of *Daphnia pulex* and Chironomidae appear at 560 cm, where marine species are absent. Brown gyttja continues up to the lake floor at 400 cm depth. The change of macrofossil taxa and sediment character indicates that the isolation boundary is at 566–565 cm depth. Terrestrial plant remains from this level were dated to 10,730-10,440 yr BP (Table 2).

Lake 11: Mellomste Snappvikvatnet 23.74 ± 0.10 m a.s.l.

The medium-sized lake Mellomste Snappvikvatnet (Fig. 8A, 380 x 180 m, 70°56.3'N 27°18.4'E) is situated at the elevation of the Main shoreline (Sollid et al. 1973). The lake record includes a sequence that dates back to the Bølling chronozone, and also a clear isolation boundary from the early Holocene. The two cores stopped in massive sediments or possibly reached bedrock. The Lateglacial part is characterised by zones with layers of brown algae (as in Lake 6, photograph in Fig. 11B).

The age of the Lateglacial sequence is documented by radiocarbon dates from core 11-1. The ages were obtained from six samples of the brown algae *Desmarestia aculeata* and a half of a *Chlamys islandica* shell (Fig. 8E, Table 2). Grey silt with seaweed layers is found in the lower part the core, from the bottom at 1181 cm up to ca. 1050 cm, at which level marine algae become much less frequent. Two samples of algae from the very bottom of the core at 1178-1179 cm were dated to 14,960-13,830 yr BP and 14,030-13,670 yr BP. Many halves of mollusk shells are found from 1120-1037 cm. A *Chlamys islandica* half from 1114.5 cm yielded 13,930–13,500 yr BP, and algae at 1040-1039 cm was dated to 13,860-13,380 yr BP.

Massive grey silt without seaweed occur up to 972 cm, where a new zone of marine algae commences and continues up to ca. 915 cm. Two algae samples from 971-972 cm gave ages of 13,340-13,080 yr BP and 13,470-13,110 yr BP, and a sample at 915-916 cm was dated to 12,910-12,260 yr BP (early Younger Dryas). Slightly dark, grey silt without seaweed continues from 915–845 cm.

Samples below 865 cm contain only marine macrofossils, e.g. macro-algae, Hydroidea, *Elphidium excavatum*, *Mytilus* byssus and cocoons of the flatworm Tricladida (Fig. 9D). At 855 cm there are hardly any macrofossils, except for numerous Chironomidae. Then, a sudden rise in limnic species is seen at 850 cm, including large numbers of cocoons identified as the lacustrine flatworm Rhabdocoela (Fig. 2, Table 1) and eggs from the freshwater crustacean *Lepidurus* (tadpole shrimp, Table 1). At this level there are no visible laminae, but the LOI rises rapidly from ca 5 % to 20 % and there is a transition from silt to gyttja (photograph d in Fig. 8F). A sample of terrestrial plant fragments from 854-850 cm dates the isolation boundary to 10,720-10,300 yr BP (Table 2). Brown gyttja continues to the lake floor at 800 cm.

A parallel core (11-2) was taken about 2 m away from site 11-1 (Fig. 8A), and used for dating the rise of *Betula* pollen at this locality. The level was detected about 20 cm above the isolation boundary, and dated to 10,390–10,160 yr BP (Table 2, K.-D. Vorren pers. comm. 2009). However, among the plant remains used for dating both the isolation boundary in this basin as well as in Nedre Snappvikvatnet, were *Betula pubescence* fruits, leaves and catkin scales, showing that the *Betula* pollen rise occurred somewhat later than the postglacial immigration of this tree to the area.

4.3.2. Holocene relative sea-level curve for Nordkinn

The relative sea level changed little prior to the rapid regression recorded between 10,500 and 10,000 yr BP (Fig. 10C). A small transgression probably took place between 10,000 and 5000 yr BP, corresponding to the Tapes transgression recorded at both Rolvsøya and Sørøya, with sea level at most rising from 10.5-13.2 m a.s.l., but probably less. Relative sea-level later fell about 10 m during the last 5000 years.

The simplest explanation for the early Holocene sea-level development at Nordkinn would be that the Younger Dryas shoreline is in fact situated at a considerably higher elevation than reported by (Sollid et al. 1973). However, the Main shoreline is represented locally by an abrasion terrace in unconsolidated sediments at the head of Oksefjorden (Fig. 8A), where it is measured at 25 m a.s.l. (Sollid et al. 1973). Distinct abrasion terraces in bedrock have also been measured at 26 m a.s.l. at the large peninsula across Laksefjorden (Fig 1A), and bedrock terraces are well-developed further inland, along the south-facing shore of the Nordkinn peninsula, where the level has been measured at about 33 m a.s.l. (Sollid et al. 1973).

These observations fit in well with the general pattern of Main line isobases mapped over a broad region in northern Norway. It therefore seems unreasonable to suggest that this level at Nordkinn is higher than reported, and we conclude that our data show that the strong land emergence following the Younger Dryas that characterises the entire Norwegian coastline was delayed for at least a millennium at Nordkinn. The reason why sea level remained at the elevation of the Main shoreline for more than a thousand years into the Holocene is unresolved.

An abration terrace in sediments measured at 13 m a.s.l. at the head of Oksefjorden (Fig. 8A, Sollid et al. 1973) was probably formed at the transgression highstand. However, Sollids (1973) shoreline diagram for Tanafjorden and the eastern side of Laksefjorden (Fig. 1A) fails to reproduce a correct development through the period, as it depicts sea level falling to 7 m a.s.l. prior to transgression. According to Møller (1987) the basins at Nordkinn are situated at the 7-8 m Tapes shoreline isobase, which is erroneous.

4.4. Magerøya

4.4.1. Basins, deposits and radiocarbon ages

We cored two lakes close to present sea level at Sarnes, a promontory of Magerøya (Fig. 1A, 70°58.7’N 25°46.9’E). At Sarnes the oldest radiocarbon date documenting human presence in northern Scandinavia has been obtained, charcoal dated to the late Younger Dryas (Blankholm 2004). We found that the lower lake at ca. 1 m a.s.l. is not yet isolated; penetration never exceeded ca. 1 m of black, sulphide-rich sediments, reflecting the current (and long-lasting) anoxic conditions at the lake bottom.

Core 9-1 was recovered from Sætervågvatnet (Lake 9) at about 2 m a.s.l., a medium-size lake (380 x 260 m) more than 15 m deep, and dammed by beach deposits. Massive glaciomarine silt with no macro-organic remains, but numerous drop stones and mollusk shells, occur from the bottom of the core at 1727 cm up to 1652 cm. A *Mya truncata* shell found at 1720 cm was radiocarbon dated to 13,740-13,390 yr BP and the uppermost shell found; a *Chlamys* *islandica* fragment at 1652 cm was dated to 13,230-12,790 yr BP (Table 2). Both mollusk shells and dropstones disappear above this level, probably reflecting lowered temperatures towards the onset of the Younger Dryas.

Homogenous light grey silt continues to 1610 cm, where there is an erosive contact to about a metre of mixed marine mud, gravel and sand that continues almost to the top of the core. We assume that this segment was deposited in a high-energy bay environment, with pervasive wave-wash during storms. The uppermost sediment at 1514–1507 cm is blackish, laminated gyttja, devoid of macrofossils. However, marine species such as Hydroidea, *Elphidium excavatum*, *Pectinaria* and marine algae were found just below the laminated part. A *Betula* twig found at 1513-1511 cm was radiocarbon dated to 2750–2490 yr BP (Table 2); this however represents a maximum age of the isolation of the lake and has not been used for sea-level reconstruction.

5. Discussion

5.1. Deglaciation chronology and Lateglacial shallow-marine environments

The marine limit in Finnmark was early shown to be diachronous, with higher (when corrected for differential rebound) and thus older levels at the outer coast. This pattern, as illustrated by shoreline diagrams (Tanner 1930; Marthinussen 1960, 1974; Sollid et al. 1973), indicates regional ice-margin recession towards the south, and has been combined with scattered ice-marginal deposits to argue for a stepwise retreat (Fig. 1A). Mapping of the marine limit to 50-60 m a.s.l. at the outermost islands led to the belief that these areas became ice-free very early (Sollid et al. 1973), corresponding to Vesterålen and Lofoten farther west (Fig. 1B, Møller and Sollid 1972; K.-D. Vorren 1978). However, since no datable material has been found at levels above the Tapes shoreline in Finnmark, nor in the ice-marginal deposits themselves, no pre-existing data constrain the chronology of ice-margin retreat.

A lake basin will, in principle, accumulate sediments from the moment it becomes ice free. A core sampler reaches bedrock or diamict if it has penetrated all strata above, with the lowermost layers yielding a close minimum age for the local deglaciation. Lake cores are therefore often used for dating ice recession in an area. However, stagnant dead-ice bodies as well as freezing to the lake floor could have caused non-deposition and/or erosion in lakes for long periods during and after deglaciation (Malmström and Palmér 1984; Allen et al. 2007;

Briner et al. 2007). Also, dating bulk samples from assumed Lateglacial lake deposits in northern Norway has been problematic due to contamination and hard-water effect (Hyvärinen 1975; Prentice 1981, 1982; Malmström and Palmér 1984; Säppä 1996; Helland 1997; Bakke et al. 2005; Paasche et al. 2007), and sufficient amounts of terrestrial plant macrofossils for AMS dating have not been found. We aimed to overcome this problem by investigating isolation lakes that were below sea-level during deglaciation. This approach has been used with success in Vesterålen (Fig. 1B, K.-D. Vorren 1978). Such lakes were not frozen to the lake floor, thus they might provide datable material from the Lateglacial.

We cored as deep as our equipment allowed in all lakes. Coring from solid lake ice rather than a raft or boat makes penetration of coarse sediment sequences possible, and from several lakes we recovered metres long sequences below the Holocene sediments. The corer stopped in each basin due to bedrock, large stones or extremely compact sediments. We believe that the lowermost sediments in several basins have been reached, and the age of these represent a minimum age for ice-free conditions at the sites.

Two types of material have been radiocarbon dated; halves of shells from the suspension feeding mollusks *Mya truncata* and *Chlamys islandica* and the remains of the brown algae *Desmarestia aculeata*. The latter is the most common brown algae around Svalbard today (Jaasund 1965), and similar layers as we have found also occur in Lateglacial marine sediments from isolation basins at Andøya (T. Vorren et al. 1988). *C. islandica* cannot live near glacier fronts, but it tolerates distal glaciomarine conditions. Both mollusk species are common in the sediments deposited in the early and mid-Allerød, but disappear above, unlike in western Norway where they have been found throughout Lateglacial sequences (Bondevik et al. 2006). All radiocarbon ages have been corrected using the present day marine reservoir age (Mangerud et al. 2006), which might be too low for the Bølling and Allerød chronozones but is still the best approximation available (Bondevik et al. 2006). The reservoir age of *Desmarestia aculeata* is probably the same as for mollusk shells (Björck et al. 1998).

We compared the obtained ages to the NGRIP ice-core δ^{18}O record (Fig. 11A; Rasmussen et al. 2006; Svensson et al. 2008; Lemieux-Dudon et al. 2010), and use these data together to estimate ages for the deglaciation sub-stages in Finnmark. The relationship between the temperatures recorded by the oxygen isotope values in the Greenland Ice Sheet and ice-sheet fluctuations in Scandinavia has certainly not always been linear (Mangerud et al. 2010), but we still assume broad correspondence between major retreat episodes of the ice-sheet margin in Finnmark and warming in Greenland. Furthermore, the palaeorecord shows that when snowfall increases over the Greenland Ice Sheet during warming climate, it still looses net mass and its margins retreat (Alley et al. 2010).

The oldest ages were obtained on a *Mya truncata* shell (Fig. 11B) from Rolvsøya and a sample of *Desmarestia aculeata* algae from Nordkinn. These were dated to 14,790-13,860 yr BP and 14,960-13,830 yr BP, respectively. The ages suggest that sedimentation began during the Bølling chronozone. The ice-core $\delta^{18}O$ record documents that a major and rapid warming episode took place around 14,600 yr BP, at the transition from the suggested 'Mystery Interval' (Denton et al. 2006) to the Bølling chronozone (Fig. 11A). We find it likely that the outer coast of Finnmark became ice free at this time, when also large stretches of the southern margin of the Fennoscandian ice sheet retreated onshore (Mangerud 1980). We assume that most of the glaciomarine sediments were deposited during rapid melting of the ice sheet in the Allerød, and we thus correlate the Outer Porsanger sub-stage to the Older Dryas cold event around 14,000 yr BP, and the Repparfjord sub-stage to the Inter-Allerød cold event around 13,000 yr BP. The Main sub-stage is represented by distinct and largely continuous marginal deposits in inner fjord areas of Finnmark (Fig. 1A) and correlate with the Younger Dryas re-advance well-known from all over Fennoscandia (Marthinussen 1961; Andersen et al. 1995).

Within the presented framework, the chronology of ice retreat has been adjusted somewhat forward in time from previous reconstructions. The last offshore recession stage in the western Barents Sea was assigned the age 16,000 yr BP and the Outer Porsanger sub-stage the age 15,000 yr BP by Winsborrow et al. (2010), whereas Landvik et al. (1998) suggested that the ice margin retreated onshore at 15,000 yr BP. Given the uncertainties of these age estimates, there is no conflict between them and our reconstruction. The Outer Porsanger stage has also been assigned an averaged maximum age of about 16-17 cal yr BP based on radiocarbon dates from sub-till deposits on the Varanger peninsula (Fig. 1., Olsen et al. 1996, L. Olsen pers. comm. 2009), but the extremely low organic content of the AMS-dated bulk samples makes it likely that these radiocarbon ages are older than the sediments.

Marthinussen (1962) correlated the Repparfjord sub-stage to the 'Skarpnes' glacial event, mapped and radiocarbon dated on a few samples of mollusk shells farther west in Troms (Fig. 1A). The Skarpnes event has been thought to occur during the Older Dryas stade (Andersen 1968; Vorren and Elvsborg 1979), but most of the radiocarbon ages fall between 14–13 cal kyr BP, and considering the accuracy of the dates, they could just as well indicate a late Allerød age and thus conform to our interpretation.

Cold conditions with little marine biological activity and little calving characterised the fjords Porsangen, Laksefjorden and Tanafjorden during the late Allerød and Younger Dryas. The very late Allerød and Younger Dryas is, at Magerøya and Nordkinn, represented by vaguely laminated, bluish-greyish silt devoid of organic content and mollusk shells and with few drop stones. The corresponding Younger Dryas segment at Rolvsøya consists of grey silty sand. The differences in contemporaneous sedimentation between the sites probably reflect both their distances to high-discharge outlets from the Fennoscandian Ice Sheet and how the melt water is distributed distally by coastal and fjord currents.

The continuous, radiocarbon dated sequences at Rolvsøya (Fig. 4) and Nordkinn (Fig. 8E) allow for sedimentation rates to be roughly calculated and compared between the Allerød and the Younger Dryas. At Rolvsøya the rate is reduced only from ca. 0.8 to ca. 0.7 mm yr^{-1}. A much more pronounced difference is seen at Nordkinn that is situated more proximal to the meltwater source; here the rate is reduced from ca. 1.9 to ca. 0.4 mm yr^{-1}, or to about a fifth. It is unlikely that falling relative sea level affected the sedimentation rates as long as the basins remained open systems, the change rather reflects the difference in meltwater production.

5.2. Influence in coastal areas by uplift of the Barents Sea seafloor

The sea-level curves from Finnmark are distinctly different from similar curves from western Norway. We extended the three new sea-level curves from Finnmark (Fig. 12A) back to the marine limit (Marthinussen 1960; Sollid et al. 1973), which, following the discussion above, probably dates to ca. 14.6 kyr BP. Two theoretical dashed curves are also included; these are based on data from Svendsen and Mangerud (1987) and Bondevik et al. (1998) and represent localities at Sunnmøre in western Norway (Fig. 1B) with similar deglaciation dates and Main shoreline elevations as the localities in this study. The sets of curves are distinctly different and indicate that much less rebound took place in western Norway than in Finnmark prior to the formation of the Main shoreline in the Younger Dryas. This is especially pronounced at the outermost locality at Rolvsøya, where the marine limit is about eight times higher than the Younger Dryas level.

Alternatively, the reported high marine limits could represent older shorelines that were overridden by glacial ice during the last glacial maximum, like has been reported from several sites in Svalbard (Lehman and Forman 1992; Mangerud et al. 1992). But in Finnmark, the marine limit is most often represented by the uppermost of a staircase of beach ridges, extending up-valley from the present shoreline. Such sites are not likely to have been protected by cold-based ice. The sheer amount of observations and their correlation over a broad region makes this interpretation improbable. However, the raised shorelines have not been studied by us and should be re-investigated with this issue in mind.

The regression rate must have slowed down or halted for some centuries during the Younger Dryas, during which time the Main shoreline was formed (Blikra and Longva 1995). We thus conclude that two separate periods of rapid emergence took place (shaded in Fig. 12A). The first uplift was mainly caused by the rapid and early deglaciation of the Barents Sea, well before the Younger Dryas. The rapid uplift in the early Holocene is a result of the deglaciation of mainland Fennoscandia.

Coast-parallel isobases in Finnmark, as well as the present uplift pattern (Sørensen et al. 1987; Ekman 1989, 1996; Danielsen 2001), have previously been taken to indicate that the demise of the Barents Sea Ice Sheet left no imprint on the rebound onshore (Elverhøi et al. 1993; Lambeck et al. 1998). However, Landvik et al. (1998) pointed out that the shoreline gradients decrease eastwards in Finnmark and that the Barents Sea Ice Sheet might have had some influence on the uplift here. Based on our new sea-level data, we calculated gradients for the 11,000 and 7000 yr BP shorelines in Finnmark and compared them, along with the Main shoreline gradient (Sollid et al. 1973), to western Norway (Svendsen and Mangerud 1987; Lohne et al. 2004; Romundset et al. 2010) and the Kola Peninsula (Snyder et al. 1997; Corner et al. 1999, 2001). This is plotted in Fig. 12B and shows a consistent pattern of much lower gradients in Finnmark and at the Kola Peninsula for the Main shoreline and the 11,000 year shoreline. For the 7000 year shoreline the gradients are similar. This also explains why the early Holocene regression around 10,000 yr BP did not reach as low in Finnmark as it did in western Norway (Figs. 10 & 12A). A relatively thin ice sheet with a gently sloping surface likely covered coastal Finnmark towards the end of the last glacial, but we think that a low-gradient ice-sheet geometry cannot explain such large differences. Also, recent observations indicate that the present-day uplift contours are in fact not strictly coast-parallel in Finnmark (Fig. 1B, Vestøl 2006; O. Vestøl, pers. comm. 2010), which could indicate that the Barents Sea uplift still influences the rebound in the area.

In order to accommodate both the rapid pre-Holocene emergence and the low shoreline gradients, we envisage a large contribution to the isostatic uplift from the Barents Sea seafloor. This is illustrated in Fig. 13, where we reconstruct the decay of the ice sheets seen along a straight-line profile running from north of Bjørnøya, across the south-western Barents Sea and Finnmark, and into Finland (Fig. 1B).

Rapid-flowing ice streams drained the interior of the Fennoscandian Ice Sheet along the large fjords in Finnmark (Ottesen et al. 2005, 2008; Winsborrow et al. 2010). Rather than calving off and disintegrating just offshore, like elsewhere along the Norwegian margin, the ice streams in northern Fennoscandia fed a large part of the marine-based ice sheet in the 300-500 m deep south-western Barents Sea (Fig. 1B). This might have caused a draw-down of ice at the outer coast, resulting in relatively thin regional ice cover (Fig. 13). The extent of allochtonous block fields almost down to sea level over large parts of coastal Finnmark (NGU 2010) further indicates cold-based (apart from the ice-stream corridors) and relatively thin ice cover here (e.g. Kleman 1994). There are no raised marine deposits at Bjørnøya (Salvigsen and Slettemark 1995), and mosses extracted from basal sediments in several lakes at the island have been radiocarbon dated to the early Holocene (Wohlfarth et al. 1995). Thus it is likely that the island remained glaciated until the end of the Younger Dryas (Fig. 13) and little uplift occurred after that. Modelling efforts have produced ice thicknesses over the Barents Sea ranging from almost no ice to a 2-3000 m thick ice sheet (e.g. Lambeck 1995; Landvik et al. 1998), with the most recent estimate suggesting about 1200 m (Siegert and Dowdeswell 2004). We reason that the loss of this mass led to uplift in the coastal parts of Finnmark.

5.3. Using macrofossils for pinpointing the isolation boundary

In this study we employed macrofossil analysis instead of the more commonly used diatom analysis to identify marine/lacustrine boundaries. Macrofossils are well preserved in lake sediments and remains from various organisms have been used for the interpretations (Fig. 2, Table 1). The boost of limnic species that occurs after lake isolation makes identification obvious in most cases. Many of these species do not tolerate saline water, and their sudden and numerous appearances indubitably reflect that highest astronomical tide no longer passed over the basin threshold. The ingression boundaries in the two basins that were submerged during the Tapes transgression are more difficult to pin to an exact level. This has also been experienced for lake records of a late-Holocene transgression in Greenland (Sparrenbom et al. 2006a), and is likely related to the slower rate of sea-level change during transgressions than during most isolation events, and to pervasive transport of limnic species to a recently inundated basin. Also, reworking of older fossils can be a problem in the higher energy marine environment. Still, this is a general weakness of the isolation basin method; we do not believe diatom analysis would yield a more accurate record of an ingression event.

Slower rates of relative sea-level change give longer periods with anoxic bottom water conditions in an isolation basin and deposition of thicker segments of laminated sediments (Anderson et al. 1985). Diatom analysis of such segments has not been straightforward, probably due to re-deposition of the small diatom frustules between the environments. Conflicting interpretations of such records have been proposed (e.g. Corner et al. 1999), with slightly offset chronologies for sea-level reconstructions as a result. We find that the macrofossils track the isolation events in Finnmark in an impeccable manner, probably partly because they are less prone to re-deposition than diatoms, leaving little doubt of where to place the boundaries.

6. Conclusions

- Three curves document relative sea-level change through the Holocene on the islands Rolvsøya and Sørøya and on the Nordkinn peninsula in Finnmark. A rapid emergence took place from ca. 11,000-9500 yr BP, followed by a transgression that inundated several of the investigated lakes between 8000 and 5000 yr BP. At the outermost locality Rolvsøya relative sea level remained at a standstill for more than 3000 years in this period.

- Radiocarbon ages of mollusk shells and macroalgae from the lowest recovered sediments indicate that the first land at the outer coast of Finnmark became ice free shortly after the abrupt warming known to have taken place around 14.6 cal kyr BP, at the onset of Bølling.

- The two terminal moraines between the outer coast and the Younger Dryas moraine are correlated to the Older Dryas ca. 14 kyr BP and to the Inter Allerød cold event ca. 13 kyr BP.

- Isostatic rebound of the seafloor of the Barents Sea influenced the sea-level history at the outer coast of Finnmark. Strong initial emergence prevailed until ca. 13 cal kyr BP as a response to the deglaciation of the Barents Sea. This further caused lower shoreline gradients in Finnmark than in comparable areas in western Norway.

- The occurrence of remains from various plants and animals indubitably documents marine-lacustrine boundaries in the investigated lake records.

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Table 1. Remains from organisms that have been found useful for analysing marine-lacustrine boundaries, and their occurrence in the various Finnmark basins. Findings of the same taxa in other sea-level studies are indicated; S-Gr. = southern Greenland (Bennike et al. 2002; Sparrenbom et al. 2006a; Sparrenbom et al. 2006b), W-Gr. = western Greenland (Bennike 1995), NE-Gr. = eastern Greenland (Björck et al. 1994a; Björck et al. 1994b; Wagner et al. 2010), Ctr-N. = central Norway (Solem et al. 1997; Solem and Solem 1997), Québ. = Québec, Canada (Miousse et al. 2003). Bracketed (x) indicates observation not identified to given species rank.

Organism	Macrofossil	Description	Size (mm)	Basin environment	Occurrence in lake basin no.											Other studies				
Marine					3	4	5	6	9	10	11	12	13	14	15	S-Gr.	W-Gr.	NE-Gr.	Ctr-N.	Québ.
Elphidium excavatum	Test	Calcareous foraminifer	0.5	Marine	x		x	x	x	x	x	x	x					(x)		(x)
Eggerelloides scabrus	Test	Agglutinated foraminifer	0.5	Marine		x	x					x						(x)		(x)
Cephalapoda	Beak	Squid	1-2	Marine	x	x		x			x									
Pectinaria	Tube	Polychaete worm	cm	Marine		x	x		x	x				x		x	x	x		
Hydroidea	Skeleton	Hydrozoan	1-3	Marine		x	x	x	x		x	x	x	x	x	x	x	x		
Sphacelaria	Algae	Brown algae	1-2	Marine	x	x	x	x		x	x	x	x	x	x	x		x		
Desmarestia aculeata	Algae	Brown algae	cm	Marine	x	x	x	x		x	x	x	x	x	x	x				
Mytilus edulis	Byssus	Blue mussel	0.5-1	Marine		x	x			x	x	x	x		x	x	x			
Tricladida	Cocoon	Flatworm	0.7	Marine	x	x	x	x			x	x				x	x			
Ruppia	Fruit	Vascular plant	2-3	Marine/ brackish		x	x													
Mallotus villosus	Vertebra	Fish	0.5-1	Marine	x	x						x				x				
Lacustrine																				
Isoëtes	Megaspore	Plant	0.4	Lacustrine		x							x			x				
Daphnia pulex	Ephippium	Crustacean	1	Lacustrine	x	x	x	x		x	x	x		x	x	x	x	x	x	x
Trichoptera	Tube	Caddis fly larvae	2-3	Lacustrine	x	x	x	x		x	x	x	x	x	x		x	x	x	
Plumatella repens	Statoblast	Bryozoan	0.7	Lacustrine	x	x	x	x								x	x	x	x	(x)
Fredericella indica	Statoblast	Bryozoan	0.6	Lacustrine	x		x	x		x	x									(x)
Cristatella mucedo	Statoblast	Bryozoan	1	Lacustrine			x	x		x	x			x		x			x	(x)
Myriophyllum	Vegetative remains	Plant	1	Lacustrine			x	x		x	x				x					
Nitella	Oogonium	Green algae	0.5	Lacustrine		x	x	x		x	x			x		x				
Chara	Oogonium	Green algae	0.7	Lacustrine				x			x					x			x	x
Chironomidae	Head capsule	Midge larvae	1	Lacustrine	x	x	x	x		x	x			x	x	x	x	x	x	x
?Centropyxis	Test	Testate amoebae	0.3	Lacustrine	x	x		x			x			x						
Difflugia pyriformis	Test	Testate amoebae	0.4	Lacustrine							x					x			x	
Oribatida	Skeleton	Soil mite	1	Lacustrine/ brackish	x	x	x	x			x		x	x	x	x	x		x	
Potamogeton	Endocarp	Plant	3	Lacustrine			x								x	x	x			x
Rhabdocoela	Cocoon	Flatworm	0.3	Lacustrine	x	x		x		x	x	x	x			x	x	x		
Lepidurus	Egg shell	Crustacean	1	Lacustrine	x	x		x		x	x		x	x		x	x	x		
Gasterosteus aculeatus	Pelvic spine	Fish	1-3	Lacustrine/ brackish		x						x	x			x	x	x		

Table 2. Radiocarbon dates. The ages have been calibrated with OxCal v4.1 (Bronk Ramsey 2009) and rounded off to nearest ten. The weighted average is calculated for the probability distribution of the calibrated age. Radiocarbon ages of marine samples have been calibrated against the Marine09 dataset (Reimer et al. 2009) using a ΔR-value of 71 ± 21, representing the present-day reservoir age for the coast of northern Norway and the Barents Sea; 437 ± 18 years (Mangerud et al. 2006). All samples were submitted to the National Laboratory for ^{14}C dating in Trondheim. Numbers starting with TUa- and TRa- refer to AMS-measurements performed at the radiocarbon dating laboratories in Uppsala and Trondheim, respectively.

Laboratory number	Lake	Core	Depth (cm)	Purpose	Material dated	Weight of submitted sample (mg)	^{14}C age (yr BP)	Calibrated age (yr BP, 2σ interval)	Weighted average (μ)	δ^{13}C (‰ PDB)
<u>Sørøya</u>										
TUa-7433	Øvre Høyvikvatnet	1-2	970-972	Betula pollen rise	*Betula pubescens* fruits, leaves and twigs	42.9	9165±50	10,490 - 10,230	10,340	-29.0
TUa-7101	Nedre Høyvikvatnet	2-1	1640-1668	Bottom sediments	Moss stems, *Betula nana* leaf fragment	19.0	4385±33	rejected		-27.0
TUa-7102	Tomasvatnet	3-4	1230-1237	Stratigraphic level	*Carex* seeds, *Betula* leaves	12.9	8713±47	9890 - 9540	9680	-25.9
TUa-7103	Tomasvatnet	3-4	1255-1257	Isolation boundary	*Drepanocladus* leaved stems	12.5	9719±53	11,250 - 10,810	11,120	-20.4
TUa-7105	Lillevatnet	4R-2	549	Tsunami deposit	Ericaceae twig	45.2	7347±40	8310 - 8020	8150	-27.2
TRa-404	Lillevatnet	4R-2	579-588	Maximum age for first isolation	Terrestrial plant remains	7.5	9367±111	11,070 - 10,250	10,610	-26.0
TUa-7106	Lillevatnet	4-5	452-453	Isolation boundary	Piece of *Betula* twig	48.3	5689±35	6610 - 6400	6470	-30.9
TUa-7107	Lillevatnet	4-5	480-484	Visual boundary	*Carex* seed, *Betula* leaves, twigs	13.7	5769±42	6670 - 6460	6570	-26.4
TUa-7108	Lillevatnet	4-5	506-507	Ingression boundary	*Juniper* twig with bark	28.4	7238±42	8170 - 7970	8070	-21.2
<u>Rolvsøya</u>										
TUa-7421	Storvatnet	5R-3	781	Tsunami deposit	*Drepanocladus* leaved stem, terr. leaf fragments	13.2	7527±54	8420 - 8200	8330	-27.6
TUa-7695	Storvatnet	5R-6	465-466	First isolation boundary	Numerous *Salix herbacea* leaves, one Ericaceae leaf, a few leaved	21.1	9624±48	11,180 - 10,770	10,970	-27.9
TUa-7692	Storvatnet	5-1	680-681	Last isolation boundary	Numerous *Empetrum nigrum* leaves, some *Salix herbacea* leaves and	5.9	4460±37	5300 - 4960	5120	-30.1
TUa-7693	Storvatnet	5-1	919-920 (I)	Ingression boundary	Small twig with bark	15.0	6752±42	7680 - 7520	7610	-24.6
TUa-7694	Storvatnet	5-1	919-920 (II)	Ingression boundary	Numerous *Empetrum nigrum* leaves, some other fragments of terr. plants	9.4	7123±41	8020 - 7850	7950	-18.2
TUa-7422	Lillerundvatnet	6-1	420	Tsunami deposit	*Salix* leaf, flower bud, small twig and some plant stems	11.0	6929±47	7920 - 7670	7760	-28.7
TUa-7696	Lillerundvatnet	6-1	448-449 (I)	Isolation boundary	*Drepanocladus* leaved stems	5.6	9825±75	11,610 - 10,900	11,260	-24.2
TUa-7697	Lillerundvatnet	6-1	448-449 (II)	Isolation boundary	Numerous *Salix herbacea* leaves, some Ericaceae leaves	14.2	9838±55	11,390 - 11,170	11,260	-27.8
TUa-7402	Lillerundvatnet	6-1	528	Stratigraphic boundary	Marine brown algae remains	8.9	11,194±51	12,750 - 12,540	12,640	-27.6
TUa-7403	Lillerundvatnet	6-1	649	Lowermost level	*Mya truncata,* one half, diameter ca. 6 cm	8838.7	12,713±54	14,790 - 13,860	14,150	2.7
TUa-7423	Badevatnet	7-1	340	Tsunami deposit	*Betula* leaves, piece of thin bark, moss stem	100.1	7298±47	8190 - 8000	8100	-31.8
TUa-8309	Badevatnet	7-1	487	Bottom of core	*Salix* and Ericaceae leaves	20.7	8101±50	9260 - 8780	9040	-27.7
<u>Magerøya</u>										
TUa-7698	Sætervågvatnet	9-1	1511-1513	Isolation boundary	Small twig with bark, most likely *Betula*	13.0	2535±31	2750 - 2490	2620	-25.8
TUa-7404	Sætervågvatnet	9-1	1718	Lowermost level	*Mya truncata* , one half, diameter ca. 5 cm	7380	12,184±51	13,740 - 13,390	13,560	1.3
TUa-8310	Sætervågvatnet	9-1	1652	Stratigraphic level	*Chlamys islandica* , fragment	528.5	11,629±63	13,230 - 12,790	13,030	2.1
<u>Nordkinn</u>										
TUa-7699	Nedre Snappvikvatnet	10-1	560-565	Isolation boundary	Small *Betula* twig with unharmed bark, *Betula pubescens* seeds, some other plant remains	12.0	9377±46	10,730 - 10,440	10,610	-27.9
TUa-7432	Mellomste Snappvikvatnet	11-2	826-830	Betula pollen rise	*Betula pubescens* fruits and leaves, mosses	11.5	9070±50	10,390 - 10,160	10,230	-30.0
TUa-7700	Mellomste Snappvikvatnet	11-1	850-854	Isolation boundary	*Betula pubescens* leaves, seeds and catkins; *Salix herbacea* leaf	23.8	9347±56	10,720 - 10,300	10,560	-27.3
TRa-411	Mellomste Snappvikvatnet	11-1	915-916	Stratigraphic level	*Desmarestia aculeata,* fragments	54.1	11,173±127	12,910 - 12,260	12,590	-26.9

Continues

Table 2. Continued

Laboratory number	Lake	Core	Depth (cm)	Purpose	Material dated	Weight of submitted sample (mg)	^{14}C age (yr BP)	Calibrated age (yr BP, 2σ interval)	Weighted average (μ)	δ^{13}C (‰ PDB)
Nordkinn										
TRa-405	Mellomste Snappvikvatnet	11-1	971-972 (I)	Stratigraphic level	*Desmarestia aculeata,* fragments	167.1	11,903±93	13,470 - 13,110	13,290	-27.5
TRa-410	Mellomste Snappvikvatnet	11-1	971-972 (II)	Stratigraphic level	*Desmarestia aculeata,* fragments	139.0	11,786±59	13,340 - 13,080	13,200	-26.8
TRa-406	Mellomste Snappvikvatnet	11-1	1039-1040	Stratigraphic level	*Desmarestia aculeata* attachment fabric (single fragment)	126.5	12,258±106	13,860 - 13,380	13,620	-27.3
TUa-7405	Mellomste Snappvikvatnet	11-1	1114.5	Lowermost large shell	*Chlamys islandica* , one half, diameter ca. 4 cm	283.1	12,379±50	13,930 - 13,500	13,750	4.4
TRa-407	Mellomste Snappvikvatnet	11-1	1178-1179 (I)	Lowermost level	*Desmarestia aculeata,* fragments	221.5	12,748±141	14,960 - 13,830	14,340	-27.3
TRa-412	Mellomste Snappvikvatnet	11-1	1178-1179 (II)	Lowermost level	*Desmarestia aculeata,* fragments	184.5	12,465±67	14,030 - 13,670	13,850	-26.6
TUa-7703	Kifjordvatnet	14-1	333-344 (I)	Isolation boundary	*Desmarestia aculeata,* fragments	15.6	4895±42	5280 - 4960	5120	-17.6
TUa-7704	Kifjordvatnet	14-1	333-344 (II)	Isolation boundary	*Betula* leaves, seeds, stems; *Ruppia* fruit	25.3	4591±42	5470 - 5050	5290	-25.2
TUa-8311	Kifjordvatnet	14-1	512-517 (I)	Bottom of core	*Desmarestia aculeata,* fragments	24.7	10,175±58	11,230 - 10,900	11,100	-23.5
TUa-8312	Kifjordvatnet	14-1	512-517 (II)	Bottom of core	Mollusc shell fragments	71.8	7075±44	rejected		-1.8
TRa-872	Kifjordvatnet	14-1	507-512	Near bottom of core	*Desmarestia aculeata,* fragments	44.3	9948±47	11,040 - 10,600	10,800	-25.3
TUa-7424	Kifjorddammen	15-1	254	Tsunami deposit	Small twig	39.1	7686±48	8580 - 8390	8480	-28.9
TUa-7705	Kifjorddammen	15-1	268.5-269	Stratigraphic level	*Drepanocladus* leaved stems	17.9	8986±58	10,250 - 9910	10,110	-31.6
TUa-7706	Kifjorddammen	15-1	270-273 (I)	Isolation boundary	*Potamogeton* seeds	126.2	9342±58	10,720 - 10,300	10,550	-18.3
TUa-7707	Kifjorddammen	15-1	270-273 (II)	Isolation boundary	*Carex* seeds; plant stems and leaf fragments	44.8	8713±64	9910 - 9540	9710	-27.0
TUa-7425	Kifjorddammen	15-1	293	Stratigraphic level	Marine algae fragments	38.8	9979±57	11,080 - 10,620	10,850	-25.0
TUa-7426	Kifjorddammen	15-1	342	Stratigraphic level	*Mya truncata* , one half, diameter ca. 5 cm	7048.1	11,954±53	13,470 - 13,200	13,340	1.7
TRa-408	Kifjorddammen	15-1	380-389	Lowermost level	*Chlamys islandica,* fragment	982.8	12,294±45	13,810 - 13,460	13,660	2.5

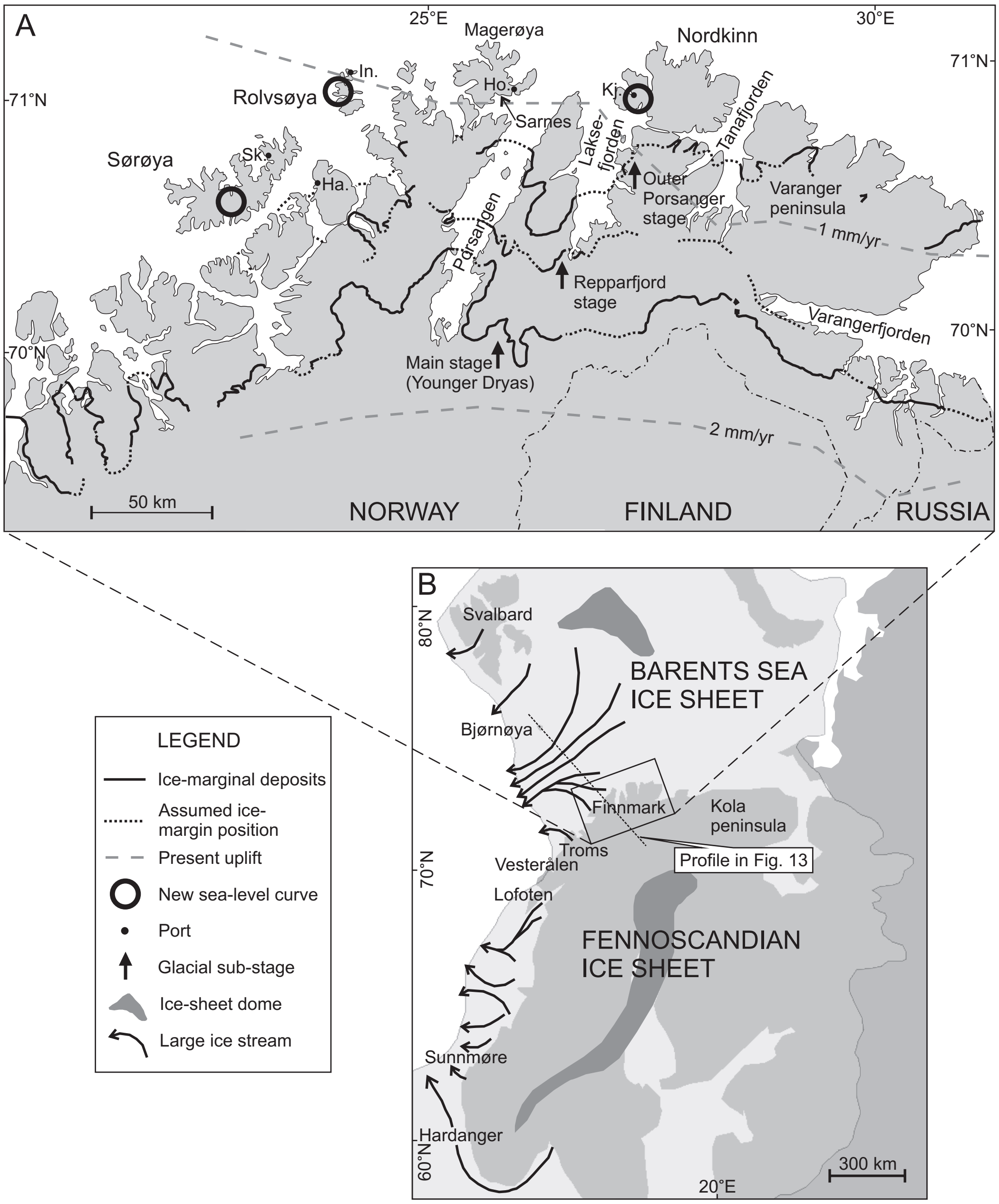


Figure 1. A. Map of the study area in Finnmark. Sites where new sea-level curves have been constructed are marked with circles. Sk. = Skarvfjorden, Ha. = Hammerfest, In. = Ingøy, Ho. = Honningsvåg, Kj. = Kjøllefjord. B. Ice coverage over Fennoscandia and the Barents Sea area at the last glacial maximum. Position of suggested dome areas and major ice streams are taken from Ottesen et al. (2005).

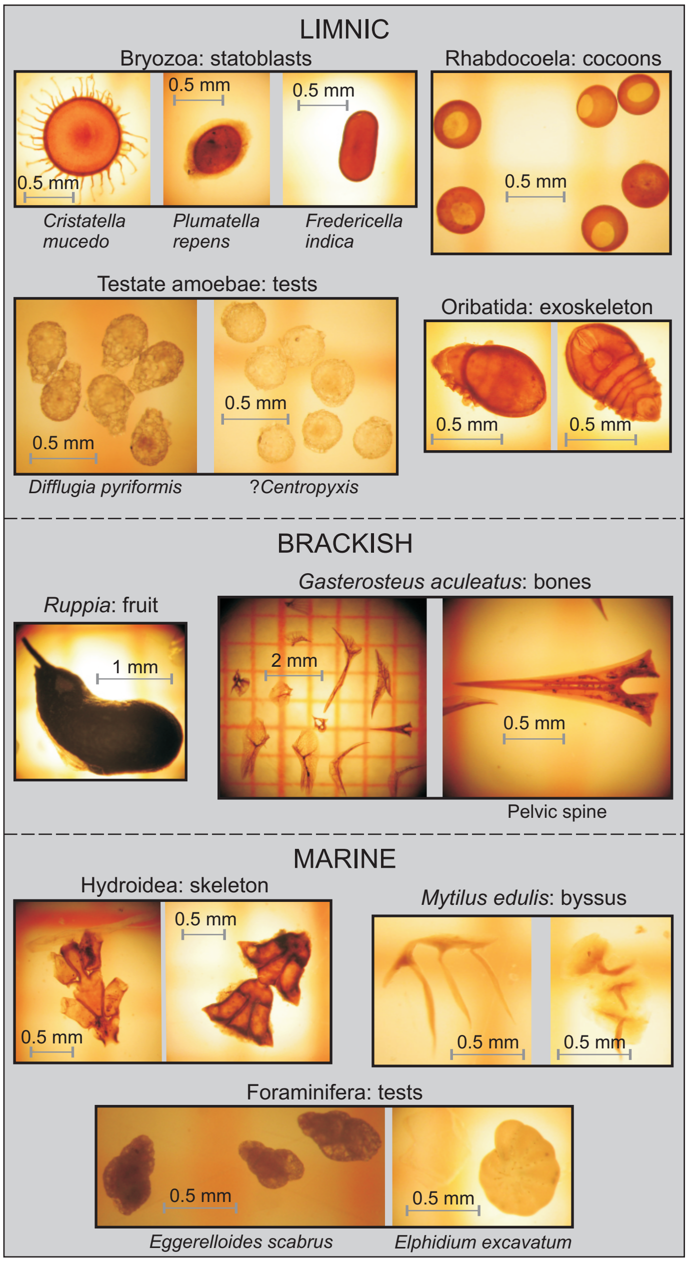


Figure 2. Examples of animal and plant remains that we found useful for the isolation basin analysis. Names of the various types of macrofossils are given.

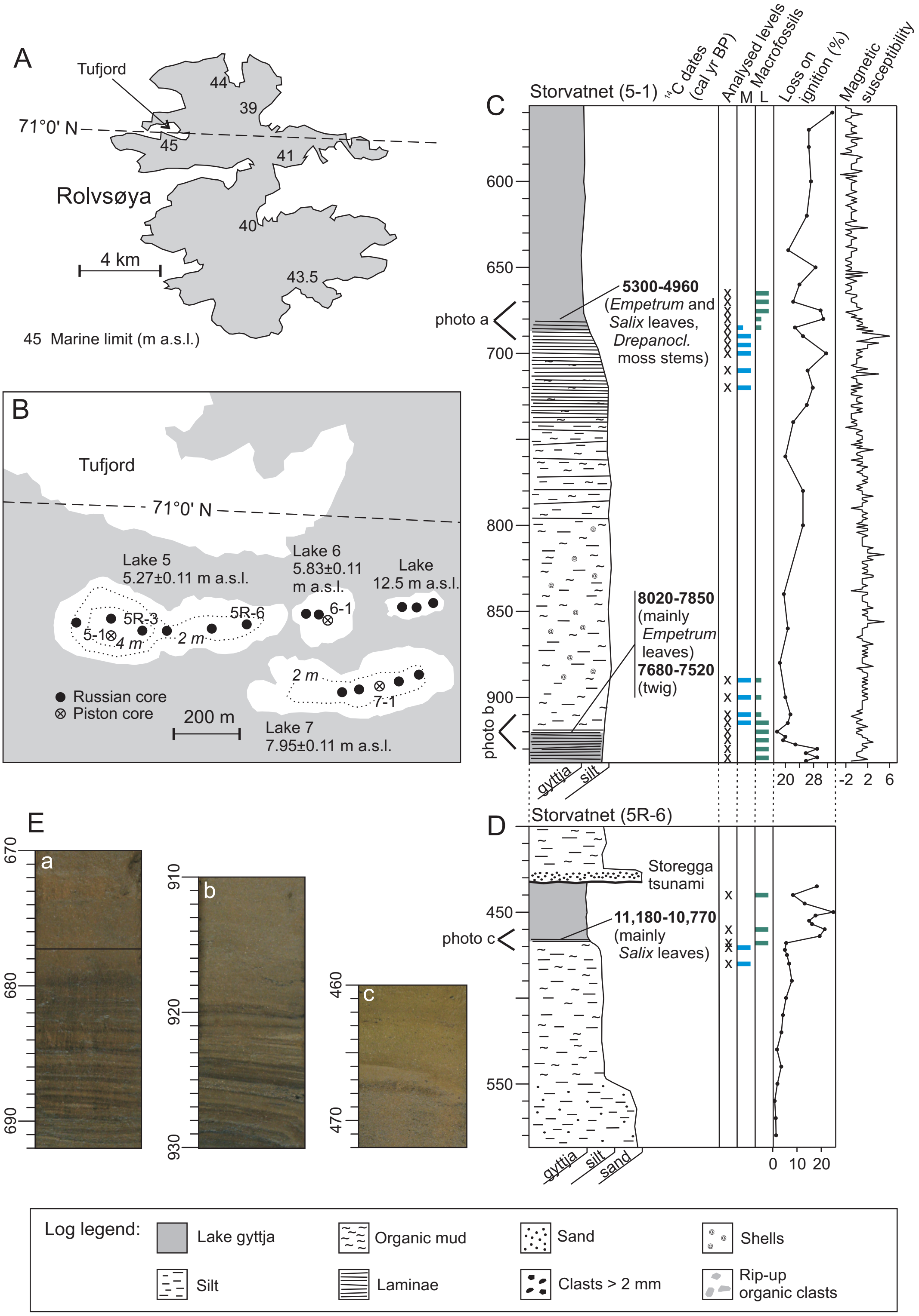


Figure 3. A. Map of Rolvsøya. Studied lakes are located in Tufjord. Marine limit elevations from Marthinussen (1960). B. The cored lake basins in Tufjord. C. Log of the stratigraphy in Lake 5 (Storvatnet) that comprises boundaries deposited at the time of ingression and isolation of the lake during the Tapes sea-level fluctuation. D. Log of core 5R-6 that includes the first isolation event, which was eroded by the Storegga tsunami at all the other core sites.

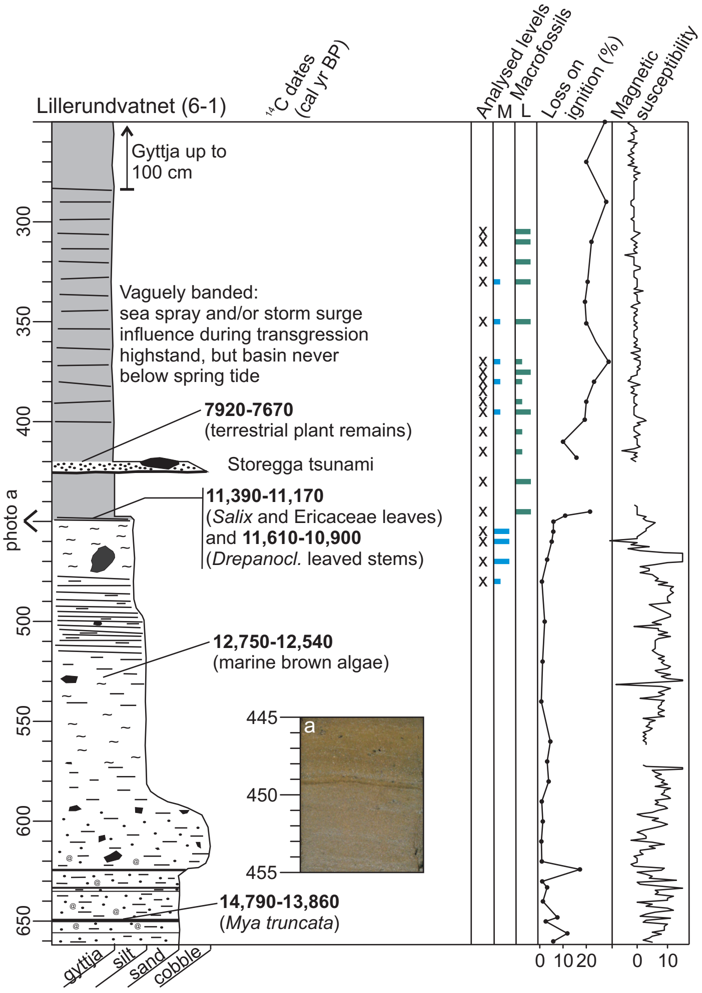


Figure 4. Log of the stratigraphy in Lake 6, comprising an early Holocene isolation and a long Lateglacial sequence.

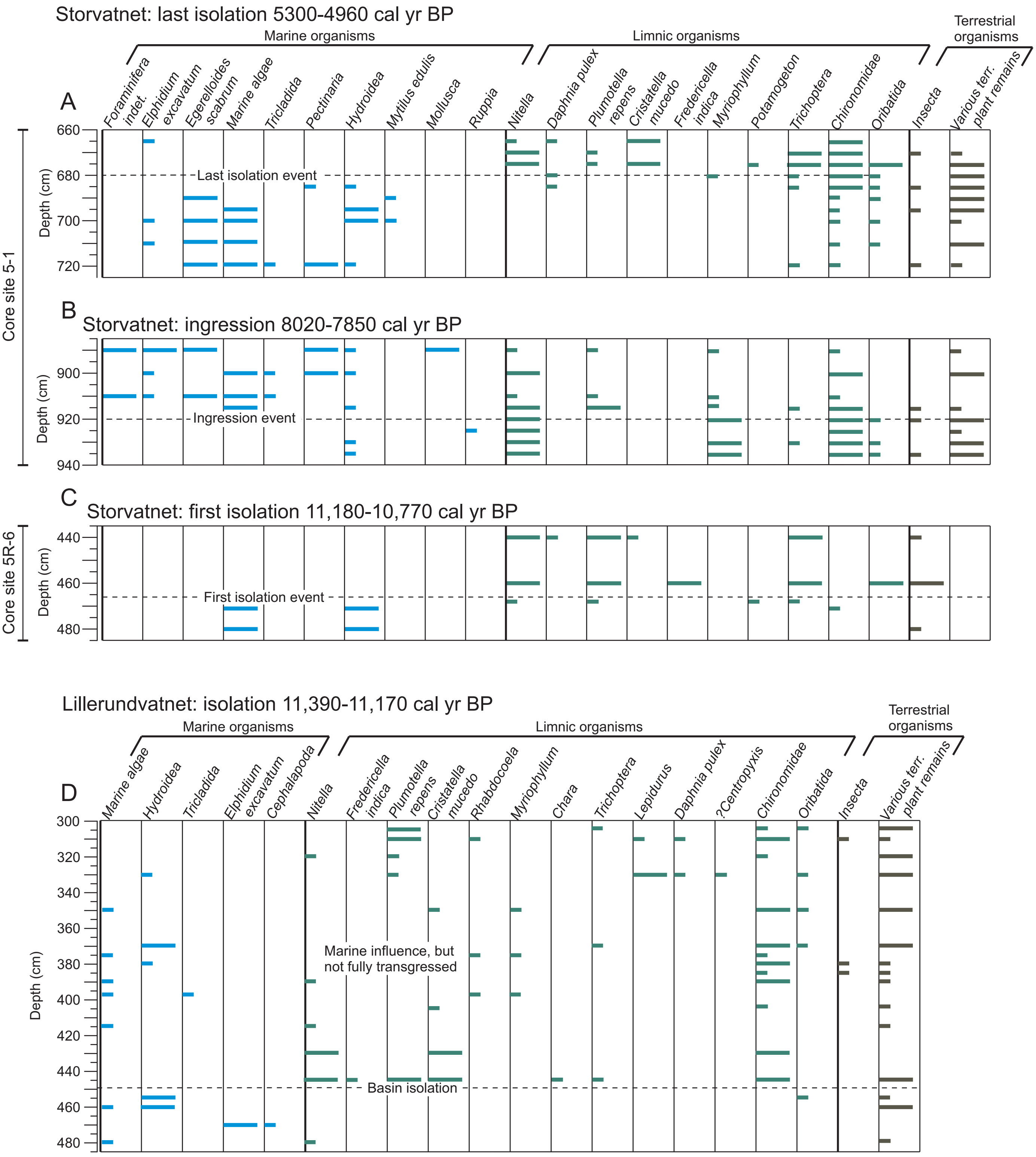


Figure 5. Diagrams illustrating the distribution of macrofossils in the records of lake 5 and 6. Long bars indicate common occurrence, short bars indicate that only few specimen were found.

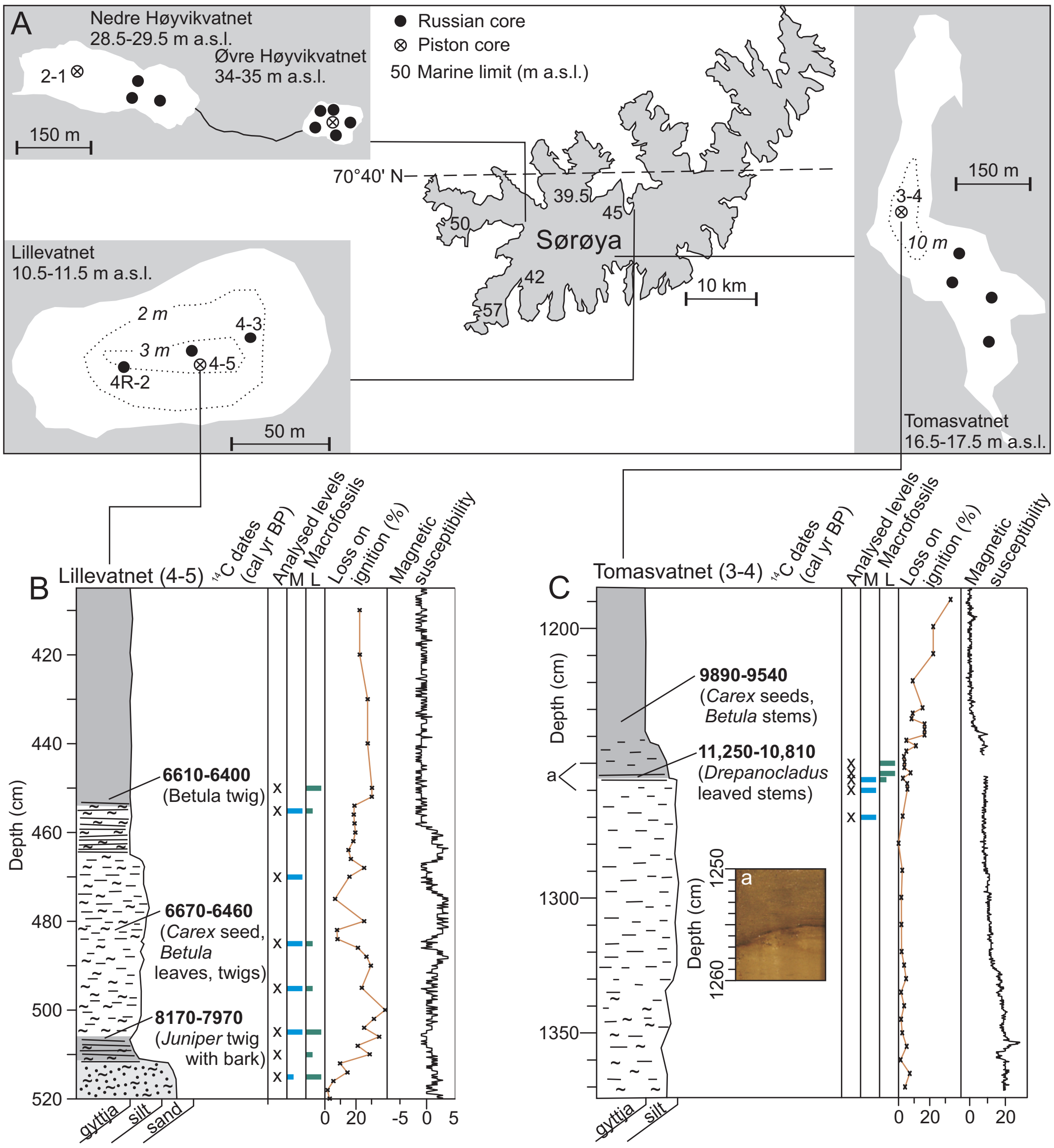
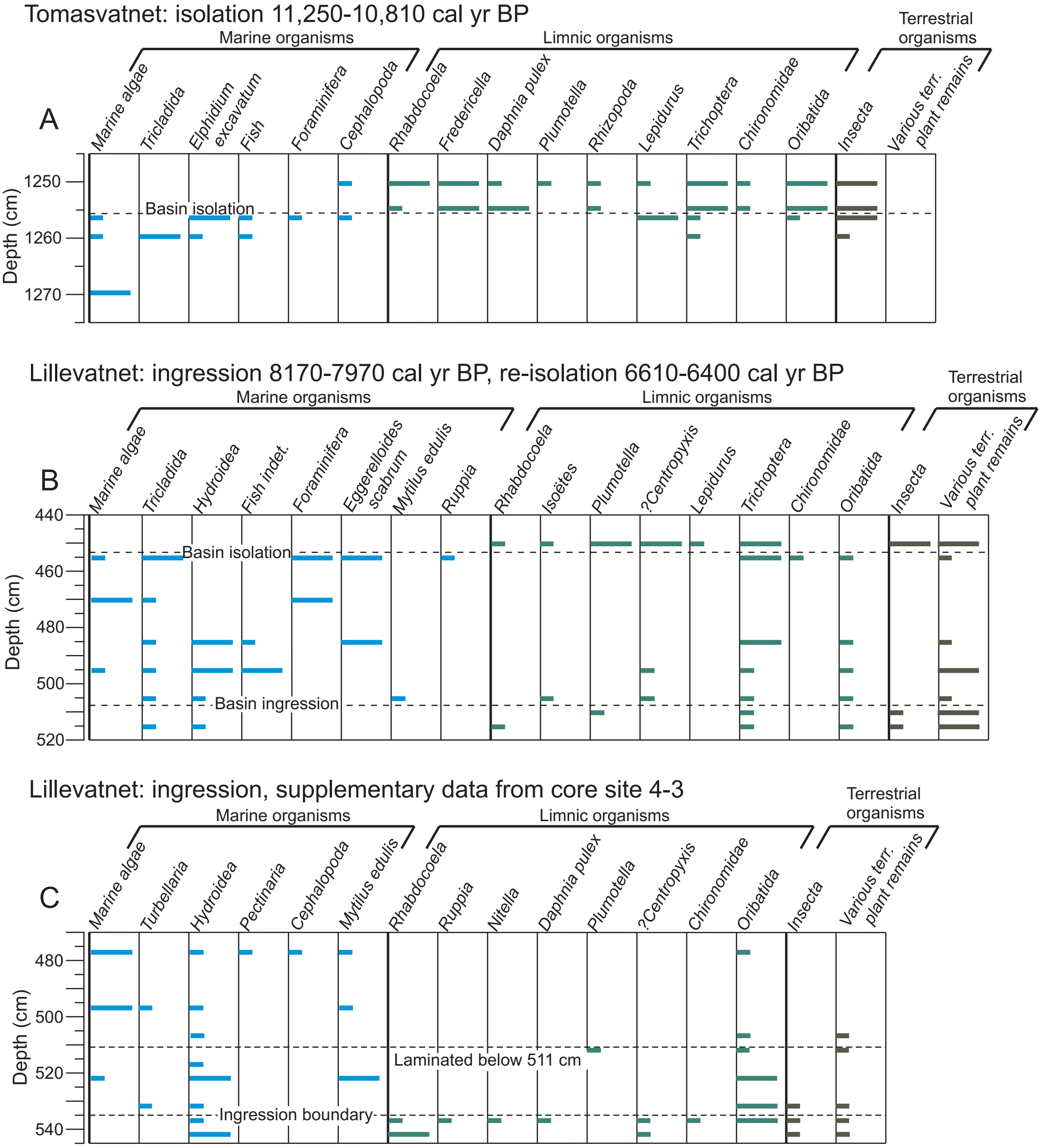


Figure 6. A. Map of Sørøya with the investigated lakes indicated. Marine limit elevation from Sollid et al. (1973). B. Log of the deposits in Lake 4 (Lillevatnet) shows the ingression and isolation during the Tapes transgression. C. Log of the deposits in Lake 3 (Tomasvatnet) that document isolation in the early Holocene.



Tomasvatnet: isolation 11,250-10,810 cal yr BP

Lillevatnet: ingression 8170-7970 cal yr BP, re-isolation 6610-6400 cal yr BP

Lillevatnet: ingression, supplementary data from core site 4-3

Figure 7. Macrofossil diagrams from Lake 3 (Tomasvatnet) and Lake 4 (Lillevatnet) at Sørøya. Long bars indicate common occurrence, short bars indicate that only few specimen were found.

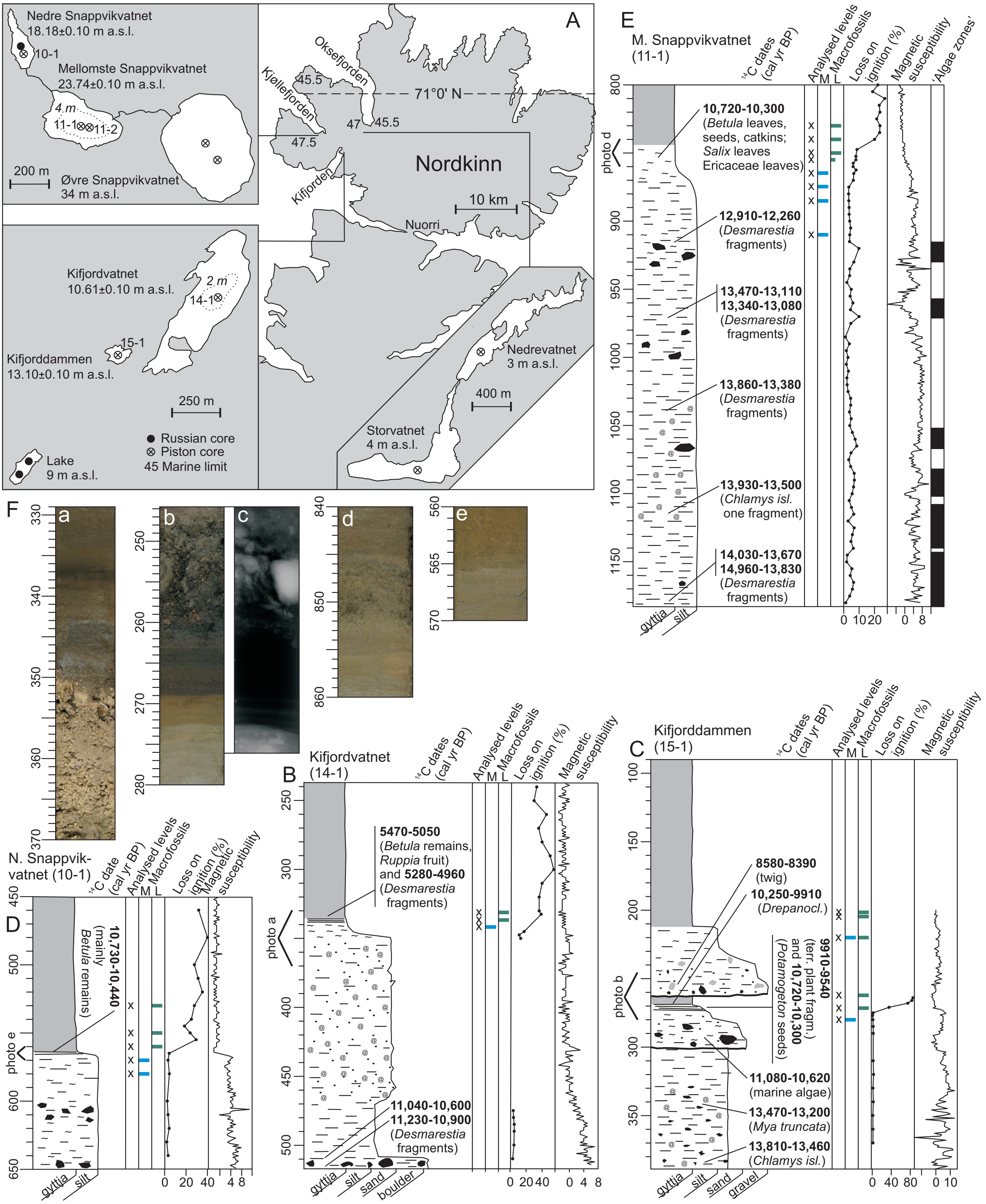


Figure 8. A. Map of the Nordkinn peninsula and position of cored lakes. Marine limit elevations from Sollid et al. (1973). B. The record of lake 14 (Kifjordvatnet). C. The record of Lake 15 (Kifjorddammen). D. The record of lake 10 (Nedre Snappvikvatnet). E. The record of lake 11 (Mellomste Snappvikvatnet).

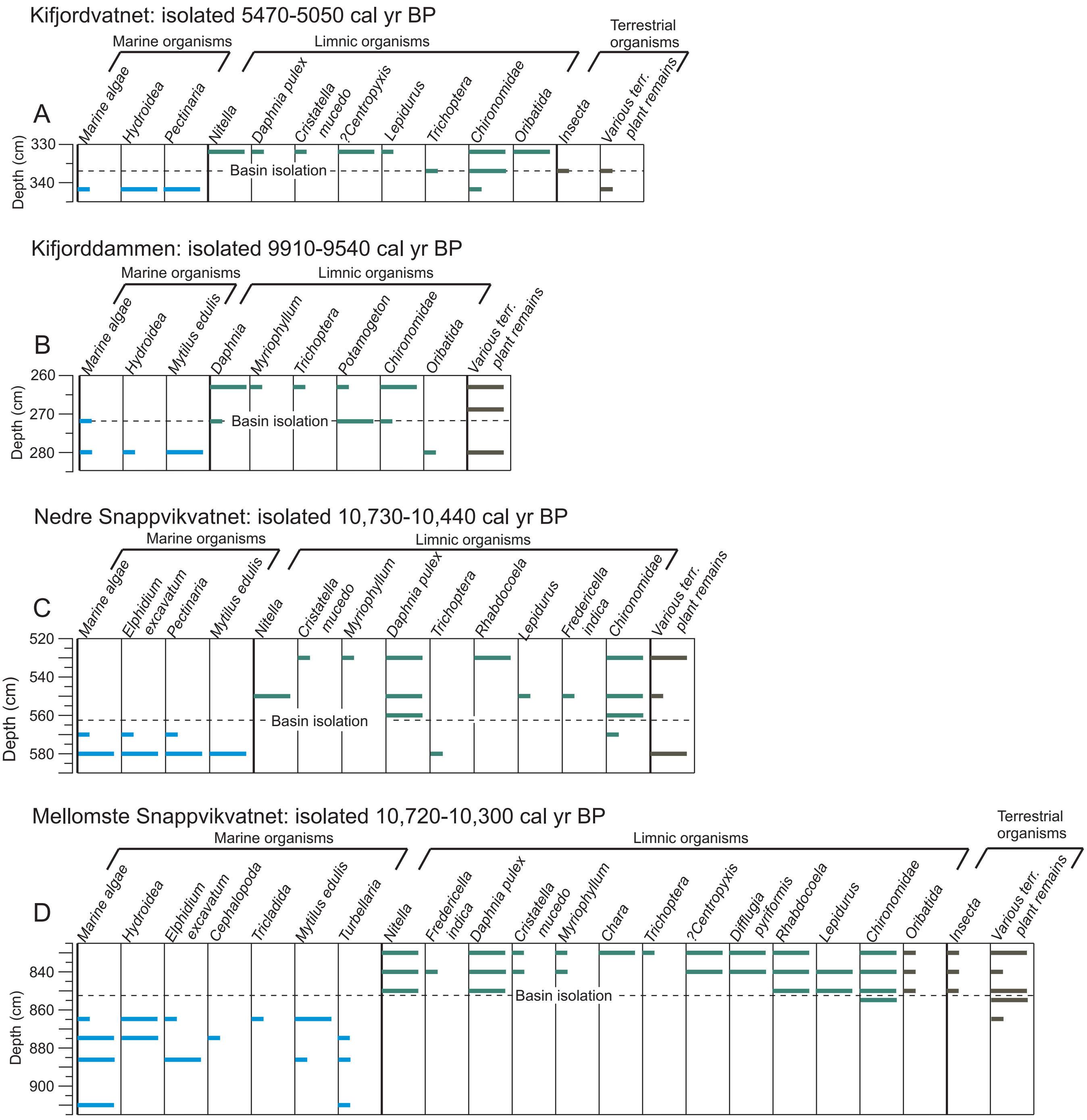


Figure 9. Macrofossil diagrams from four lakes at Nordkinn. Long bars indicate common occurrence, short bars indicate that only few specimen were found.

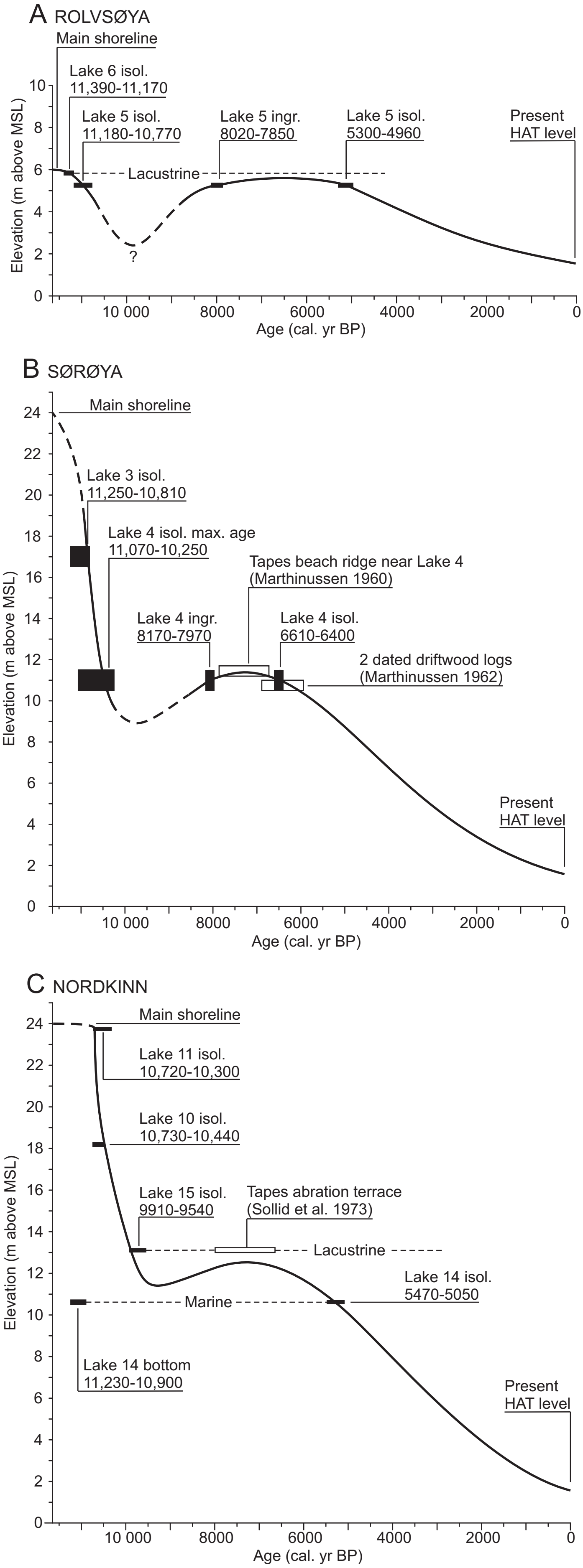


Figure 10. A. Relative sea-level curve from Rolvsøya. B. Relative sea-level curve from Sørøya. C. Relative sea-level curve from Nordkinn.

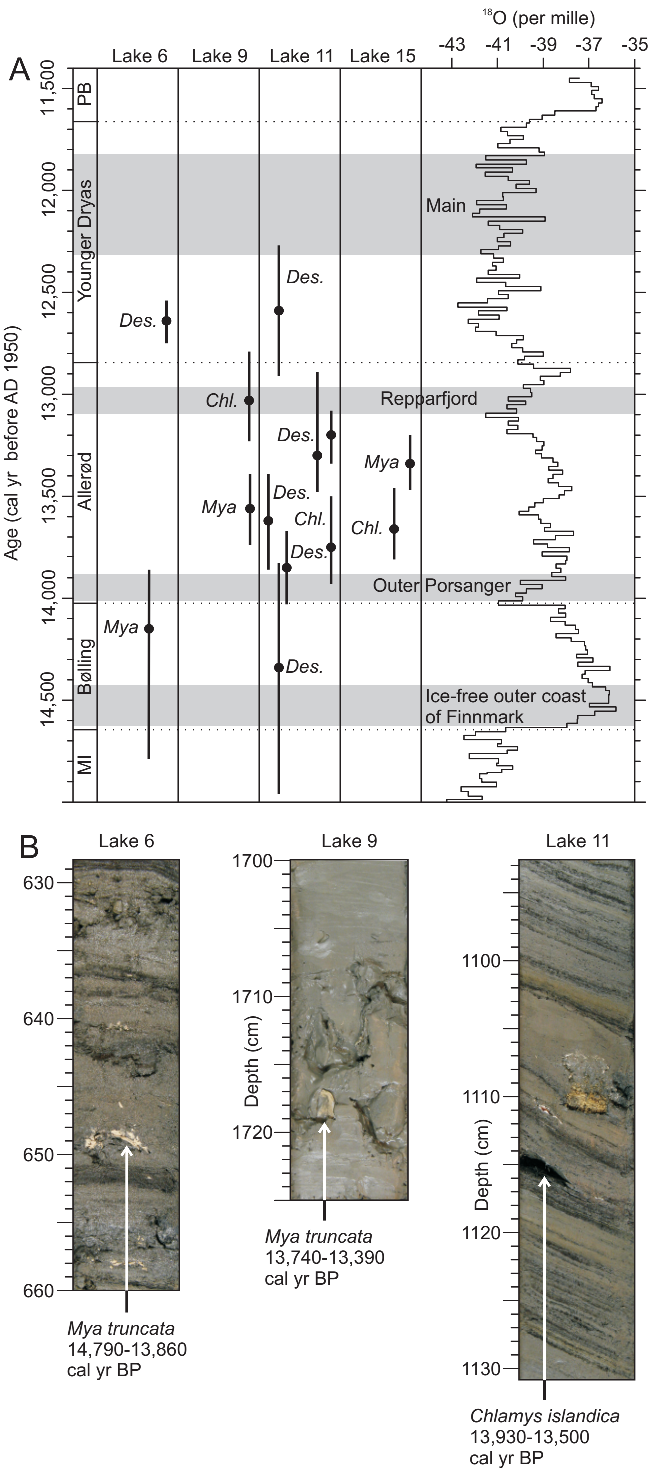


Figure 11. A. Calibrated radiocarbon ages of shells and macroalgae from the pre-Holocene sequences. The dot represents the statistically most probable age after calibration, whereas the line covers the 2σ age interval. Shaded areas indicate timing of events. Oxygen isotope values and chronozones are based on the GICC05 time scale from the NGRIP ice core (Rasmussen et al. 2006; Lemieux-Dudon et al. 2010). MI = Mystery Interval (Denton et al. 2006), PB = Preboreal. B. Pictures of some of the cores with dated samples.

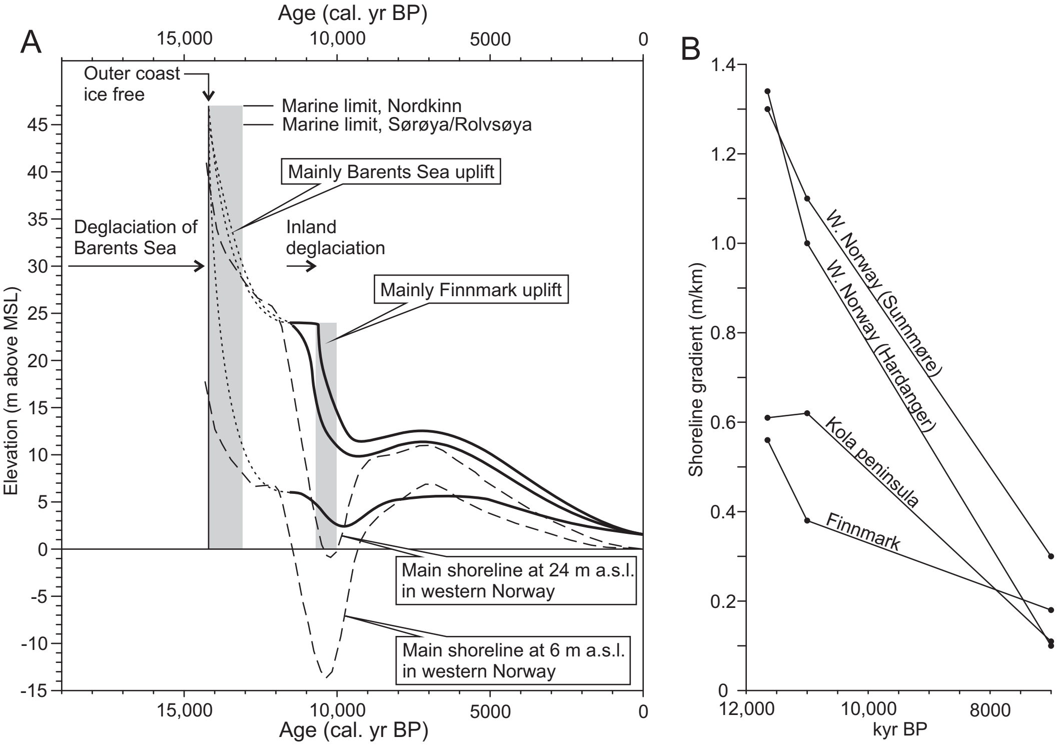


Figure 12. A. Compilation of the three new sea-level curves, extended back to the deglaciation and compared to theoretical curves from western Norway (Svendsen and Mangerud 1987; Bondevik et al. 1998). Periods of rapid emergence are shaded, and the origin of the uplift indicated. B. Change in shoreline gradients during the first half of the Holocene in four different regions; Sunnmøre (Svendsen and Mangerud 1987), Hardanger (Lohne et al. 2004; Romundset et al. 2010), Kola peninsula (Snyder et al. 1997; Corner et al. 1999; Corner et al. 2001) and Finnmark (Sollid et al. 1973, this work).

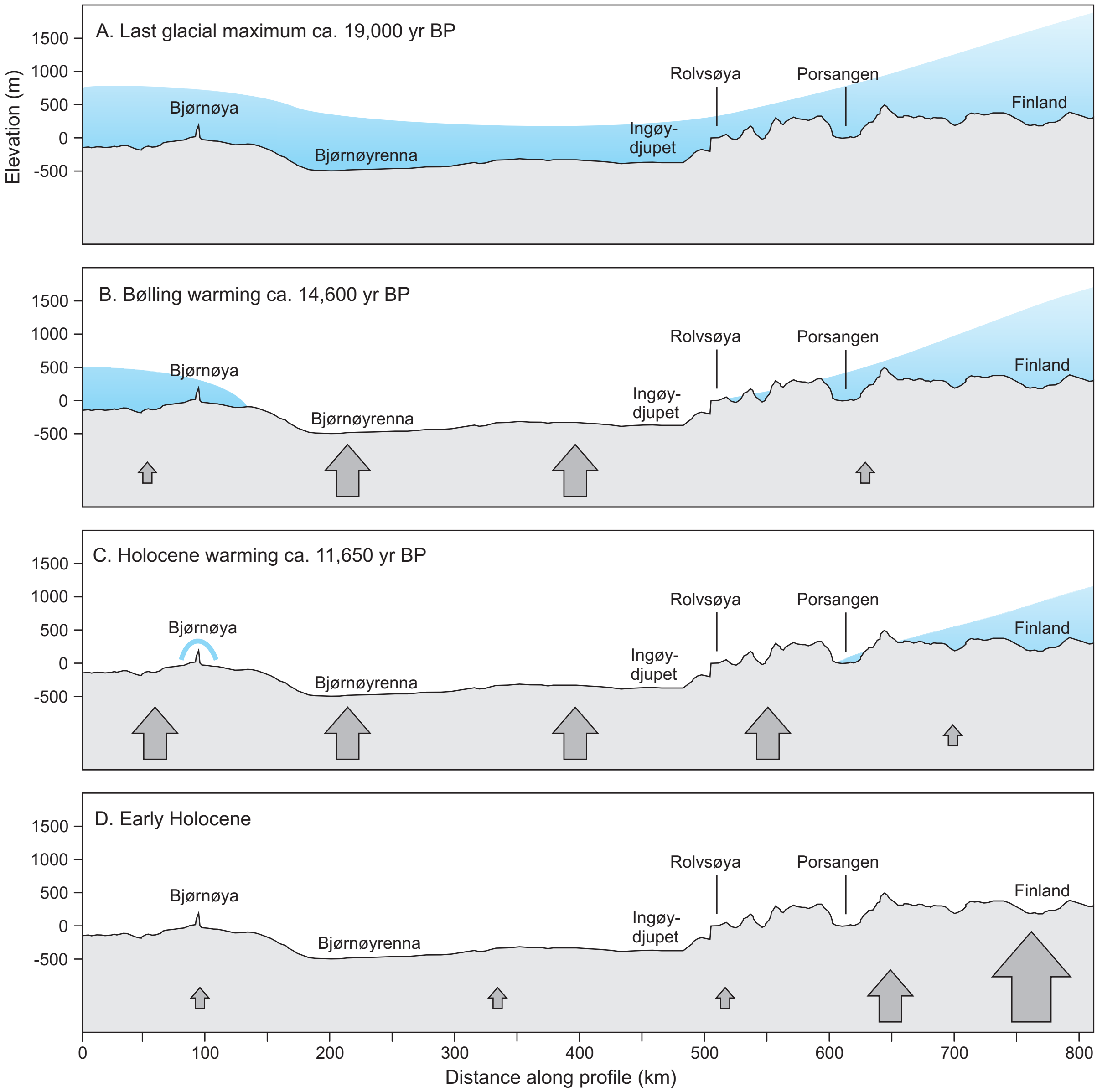


Figure 13. Conceptual model for the deglaciation and uplift history of the southwestern Barents Sea and Finnmark. Large arrows indicate strong uplift, small arrows indicate less uplift. The straight profile line extends from north of Bjørnøya south-eastwards and crosses the Finnish border, for location see Fig. 1.