Spatio-temporal patterns in late-glacial and Holocene vegetation and climate of Finnmark, northernmost Europe

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Abstract

Precisely-dated records of palaeovegetation and reconstructed palaeoclimate are presented from three lakes in northernmost Finnmark. The lakes lie adjacent to the southern shore of the Barents Sea and are located along a west–east transect. The three records are used to reconstruct spatial patterns in regional vegetation and climatic history since 13,900 cal yr BP. Longer-term shifts in treeline position and in the position of the *Pinus–Betula* ecotone are recorded. In addition, especially during the regional Holocene thermal maximum, the latter exhibited strong periodic fluctuations. The number and strength of these fluctuations that were recorded at each of the three sites differed systematically, with fewer and weaker fluctuations seen at the easternmost site, in particular. The patterns revealed are used to test the hypothesis that variations in the strength of the North Cape Current have been of primary importance as the proximal driver of climatic variability in the region since deglaciation. The results provide strong support for this hypothesis during the Holocene, the strong periodic fluctuations during the regional Holocene thermal maximum in particular being consistent with the proposed mechanism. During the late-glacial and earliest Holocene the patterns are less clear, but nonetheless also consistent with the proposed mechanism. Further work on precisely-dated marine sediment cores will be necessary to understand the factors leading to the periodic and longer-term variations in strength of the North Cape Current.

Keywords

North Cape Current; Barents Sea; treeline; *Pinus–Betula* ecotone; periodicity.

1. Introduction

Principally as a result of their proximity to the North Cape Current (NCaC, Ingvaldsen, 2005), a warm surface current in the southern Barents Sea that is one of the ultimate branches of the North Atlantic Current (Figure 1(a)), the northern coastal peninsulas of Finnmark, the northernmost parts of mainland Europe, have an anomalously mild present climate compared to more inland areas of northern Fennoscandia that lie to the south. Holocene palaeoclimate and ecosystems in this coastal region are thus expected to have been particularly sensitive to variations in the strength of these ocean currents, that in turn are sensitive to the varying strength of the Atlantic meridional overturning circulation (AMOC) evident from studies of marine sediments (Bianchi and McCave, 1999). Previous work at a small lake on Norkinnhalvøya (Figure 1(b)), in central northern Finnmark (Allen et al., 2007), has provided evidence of millennial variability, both in Holocene palaeoclimate and in the position of the northern limit of *Pinus sylvestris* (Scots Pine) (nomenclature for vascular plants follows Mossberg and Stenberg, 2003), the species of coniferous tree that extends furthest north in Fennoscandia, forming the northernmost taiga in this region (Figure 1b).

Whilst such evidence from a single locality confirms that regional climate and ecosystems exhibited millennial variability throughout the Holocene, it cannot provide evidence of any spatial pattern in this variability. Spatial patterning is to be expected, however, if the underlying cause of the regional variability is varying strength of the AMOC, and hence of the NCaC. Increased strength of the NCaC is likely to result also in increased eastward extension of warm surface water, with the converse happening when the current weakens. If this is the case, and if the variations observed on Nordkinnhalvøya are related to varying strength of the NCaC, then similar evidence of variations in climate and ecosystems is expected at other sites along the Finnmark coast. Furthermore, unless the fluctuations in strength and penetration of the NCaC were of consistent magnitude, the variations in climate and ecosystems seen along the Finnmark coast would not be expected to be consistent in magnitude with longitude. On the contrary, if at some times the NCaC reached only to western Finnmark, then only at sites on the western peninsulas would its influence be likely to be apparent, whilst if at other times it penetrated beyond eastern Finnmark, then its influence is likely to be apparent at sites east to Varangerhalvøya, the easternmost peninsula of the Finnmark coast.

In order to explore whether there is evidence of such longitudinal variability in the magnitude and spatial extent of Holocene variations in climate and ecosystems, further comparable records are required from sites at locations to the west and/or east of the previously studied site. Comparison of these records with that from Nordkinnhalvøya will provide evidence of the extent to which the variability observed at the central site also is apparent at other sites in the region, and hence of the extent to which this variability is, as was argued previously, a regional rather than a local signal. More importantly, such comparisons may also provide evidence of fluctuations observed at the Nordkinnhalvøya site that are not seen further east and/or of additional fluctuations seen to the west that are not recorded by the site on Nordkinnhalvøya. Critical for any such comparisons, however, will be that each record has its own independent high-resolution chronology. Only in this way can comparisons be made objectively and without recourse to 'wiggle matching' and its associated hazard of circular reasoning.

We present here the results of pollen analyses at two further lakes, one in western Finnmark on the island of Magerøya and one in the east on Varangerhalvøya (Figure 1(b)). Together with the site examined on Nordkinnhalvøya, these sites form a west–east transect extending for > 150 km and spanning most of the Finnmark coast. We also present new high-resolution age–depth models for all three sites. These provide the basis for investigating the extent to which the three records exhibit coincident fluctuations in ecosystems and reconstructed climate, and also allow us to explore the extent to which the records show evidence of periodicity in these fluctuations. The results are used to infer spatial and temporal patterns in regional Holocene climate and ecosystems and to explore the extent to which these are consistent with fluctuations in the strength of the AMOC and hence of the NCaC.

2. Methods

2.1. Sites and sampling

The western site is located on the island of Magerøya, best known because its northernmost point, Nordkapp (71° 10′ 21″ N, 25° 47′ 40″ E), is often considered to be the northernmost point in Europe, as well as marking the boundary between the Norwegian and Barents Seas. The lake is unnamed on the 1:50,000 topographic map (Topografisk Hovedkartserie—M711, Blad 2037 II 'Nordkapp'; Statens Kartverk, N–3500 Hønefoss); we refer to it as liten Čap'pesjav'ri. It is located near the west coast of Magerøya, *ca*. 2·5 km south of the hamlet of Gjesvær (Figures 1(b) and 2(a); 71° 4′ 28″ N, 25° 22′ 5″ E, 41 m above sea level (a.s.l.)) and has a surface area of *ca*. 2·5 ha. It is one of several small lakes linked by a small stream flowing from Čap'pesjav'ri (56 m a.s.l.) to the sea. The local bedrock is principally metamorphosed Late Proterozoic to Cambrian age sandstones, with quartzite, amphibolite and conglomerate layers (Siedlecka and Roberts, 1996). The eastern site lies close to the north coast of Varangerhalvøya, near the western shore of Kongsfjord and *ca*. 2·5 km south of the eponymous hamlet (Figures 1(b) and 2(b); 70° 41′ 57″ N, 29° 17′ 41″ E, 51 m a.s.l.). It too is unnamed on the 1:50,000 topographic map (Topografisk Hovedkartserie—M711, Blad 2336 II 'Kongsfjord'; Statens Kartverk, N–3500 Hønefoss); we refer to it as over Kobbkrokvatnet. It has a surface area of *ca*. 1·7 ha and is one of three small lakes, the uppermost at 64 m a.s.l., connected by a small stream flowing into Kobbkrokvatnet at 48 m a.s.l.. The local bedrock is mostly dark grey sandstone, alternating with layers of grey-black mudstone and shale, assigned to the Barents Sea group and marginal to the rocks of the Caledonian orogeny (Siedlecka and Roberts, 1996). The central site, referred to as over Gunnarsfjorden (Allen et al., 2007), is located close to the east coast of Nordkinnhalvøya, the peninsula that extends to the northernmost mainland point in Europe at Kinnarodden (71° 8′ 2″ N, 27° 39′ 0″ E), *ca*. 4·0 km south of the hamlet of Gamvik (Figures 1(b) and 2(c); 71° 2′ 18″ N, 28° 10′ 7″ E, 78 m a.s.l.). With no discrete inflow(s) and a single small outlet stream to the south, the lake has a surface area of *ca*. 5 ha. Its catchment is dominated by metamorphic rocks, principally micaceous and garnetiferous schists and slates of Caledonian age (*ca*. 550 – 400 Ma) (Siedlecka and Roberts, 1996).

The present climate at all three sites is Arctic–maritime (Table 1), temperatures being moderated by the influence of the adjacent ocean so that winter temperatures are much milder and summer temperatures cooler than at localities to the south in central Finnmark. Precipitation is distributed more or less evenly between winter and summer and there is no seasonal moisture deficit. All three sites are today located in tundra, a major component of which are dwarf-shrub communities dominated by *Empetrum nigrum* ssp. *hermaphroditum* (Crowberry), with *Vaccinium vitis-idaea* (Cowberry), *V. uliginosum* (Bog Bilberry), *V. myrtillus* (Bilberry) and *Betula nana* (Dwarf Birch) as frequent and locally co-dominant components. The latitudinal treeline, formed by *Betula pubescens* ssp. *czerepanovii* (Mountain Birch), lies *ca*. 70 – 100 km south (Figure 1(b)), although even there the sub-Arctic birch woodlands are restricted to lower elevations. The northern limit of *Pinus sylvestris* taiga lies a further *ca*. 30 – 60 km to the south. Although outlying stands of *B. pubescens* ssp. *czerepanovii*, for example at Oksefjorden on Nordkinnhalvøya (70° 57′ 41″ N, 27° 34′ 12″ E), and of *P. sylvestris*, for example at Børselv on the eastern shore of Porsangen (70° 18′ 45″ N, 25° 34′ 48″ E), occur well north of the treeline and of the *Betula* – *Pinus* ecotone, respectively, these stands occupy locally warmer sites within the landscape and are considered to be relicts from the earlier Holocene when both birch woodlands and pine forests extended further northwards.

All three sites lie beyond the ice margin mapped by Sollid *et al*. (1973) for the Outer Porsanger sub-stage. Liten Čap'pesjav'ri, on Magerøya, also lies beyond the ice margin mapped for the Risvik sub-stage, whilst over Gunnarsfjorden lies within the zone of the Risvik sub-stage moraine and the eastern site, over Kobbkrokvatnet, lies within the Risvik sub-stage ice limit and just outside the Outer Porsanger moraine that runs along the ridge to the south of the site. The Outer Porsanger and preceding Risvik sub-stages are the earliest sub-stages of the last deglaciation in Finnmark; both pre-date the late-glacial interstadial (Greenland interstadial 1) and are dated to *ca*. 15,000 cal yr BP (Romundset et al., 2011) and *ca*. 16,000 cal yr BP (Winsborrow et al., 2010), respectively. Sollid *et al*. (1973) also mapped the marine limit. On the basis of the maps and data that they present, two of the sites lie marginally below the local marine limit. At 41 m a.s.l., liten Čap'pesjav'ri is at least 3 m below the closest points where the marine limit elevation is reported by Sollid *et al*. (1973) (44m at Yttervaer, 6 km south at 71° 1′ 14″ N, 25° 21′ 14″ E; 47·5 m at Austerbotn, 7·5 km south-east at 71° 2′ 5″ N, 25° 32′ 11″ E), whilst over Kobbkrokvatnet, at 51 m a.s.l., is at least 2·5 m below the closest points with reported marine limit elevations (53·5 m at Straumen, *ca*. 2 km south-east at 70° 41′ 22″ N, 29° 19′ 35″ E; 54·5 m east of Homvdneset, *ca*. 2km south at 70° 40′ 40″ N, 29° 16′ 27″ E). At 78 m a.s.l., however, over Gunnarsfjorden is apparently substantially above the local marine limit (45·5 m at Tverviken, *ca*. 3 km east north-east at 71° 2′ 47″ N, 28° 14′ 55″ E). Relative sea-level fell quickly from the marine limit and all sites remained above any direct tidal influence throughout the Holocene, all three being well above the Tapes (mid Holocene) transgression maximum that in Finnmark did not exceed 20 m a.s.l. (Corner et al., 2001).

Sediments were cored in April 2000 at over Gunnarsfjorden and in March/April 2001 at the other sites. Cores were taken from the winter ice cover, the thickness of which ranged between 0·75 and 1 m, and were collected from the deepest part of each basin that was located by boring a series of test holes through the ice. Coring locations were recorded using a handheld GPS receiver (Garmin e-Trex). In each case, two overlapping cores were collected, *ca*. 0·5 m apart, using a 7·5 cm diameter Wright-modified square-rod piston corer (Wright, 1967) able to collect 1 m length core segments. Coring depths were adjusted to ensure that junctions between segments in the second core collected fell close to the middle of segments in the first. Coring holes were cased using 15 cm diameter drainage pipe so as to be able to collect near continuous cores. Core segments were extruded in the field and key lithological features noted before wrapping them in plastic film and aluminium foil. A 'perspex tube' piston core was also collected at each site to enable sampling of the upper unconsolidated sediments from just below the sediment–water interface. The latter cores were sampled at 1 cm intervals in the field, samples being stored in individual self-seal polythene bags. These cores overlapped completely the conventional piston cores, ensuring that the entire sequence could be sampled. After transport to Durham, core segments were stored at 4°C except when being sampled. Cores were split, photographed and sediment lithology logged in detail in the laboratory. Sub-samples (0·7 cm diameter, 0·515 cm^3) for pollen analysis and for measurement of % dry weight loss upon ignition were taken at intervals of between 2 and 8 cm. Sampling extended from the sediment–water interface to the base of the lacustrine sediments in each case.

2.2. Chronology

A series of AMS ^{14}C age determinations was obtained for each core, ^{14}C measurements being made on terrestrial macrofossils extracted from 1 or 2 cm depth slices of half the core (*ca*. 22 or 44 cm^3). Purified water was used to wash the sediment through a 250 μm mesh sieve, retained material being examined using a Leica Wild M3C stereo-magnifier. Macrofossils were picked out and identified as completely as possible before drying at 100°C and wrapping in aluminium foil or storing in a glass vial for submission to the dating laboratory. A sub-set of samples for measurement was selected initially for each site on the basis of the sediment lithology and key features of the pollen diagram. The age estimates obtained for these samples were then used to generate age–depth models in calibrated years before present for each site, using Bchron (Parnell et al., 2008, see http://cran.r-project.org/web/packages/Bchron/index.html). These age–depth models were then used to identify those parts of each sediment sequence where age uncertainty remained greatest, and further samples submitted from appropriate depths with the aim of minimising remaining uncertainty. This process was repeated through three iterations, thus gaining greatest benefit, in terms of minimised age uncertainties, from the number of ^{14}C age determinations available. Final age–depth models, based upon all the available age estimates, were also constructed using Bchron.

2.3. Pollen analysis and palaeovegetation

Samples for pollen analysis were prepared by conventional methods (NaOH, 180 μm sieve, HCl, $ZnCl_2$ density separation, acetolysis, staining with safranin, dehydration and suspension in 2000 cs silicon fluid). A measured volume of a suspension of known concentration of pollen of *Eucalyptus* sp. was added to each sample before the first chemical treatment so as to enable pollen concentrations, and hence pollen accumulation rates, to be estimated. Material retained by the 180μm sieve was examined and any identifiable macrofossils recorded. Extracts were mounted on glass slides and examined using a Leica DM/LM microscope at 400x magnification; fine detail was examined at 1000x magnification when necessary. Published keys and guides (Erdtman et al., 1961; Moore et al., 1991) were used to aid in identification of pollen and spores, critical identification being confirmed by comparison with reference material. Nomenclature for pollen and spore taxa follows the conventions proposed by Birks (1973), Mossberg and Stenberg (2003) being the source for the underlying plant taxon names. Pollen diagrams were plotted using Tilia© (v. 1.7.16), data being presented as percentages (Figures 6, 7 and 8) with terrestrial pollen taxa expressed as percentages of total land pollen (ΣTLP) and aquatic pollen taxa, *Sphagnum* and Pteridophyte spores expressed as percentages of ΣTLP + the relevant group sum. Rarer terrestrial pollen taxa have been grouped according to their plant functional type (PFT). Overall pollen accumulation rates are also shown on these diagrams; pollen accumulation rate diagrams for all taxa shown on the percentage diagrams are presented as Figures S1 – S3 (Supplementary Information).

2.4. Palaeoclimate reconstruction

Quantitative palaeoclimate reconstructions were made from the pollen data using the 'RS11' surface sample dataset, this being the 'RS10' dataset of Haslett *et al*. (2006) augmented with a series of surface samples from lakes in Finnmark (Allen et al., 2007). The method of direct analogues (Cheddadi et al., 1998; de Vernal and Hillaire-Marcel, 2000) was used, limiting the selection of potential analogues to those surface samples with annual temperature sum < 1200 °C days above 5°C, hence to those located beyond treeline or in Boreal or montane forests. This restriction was necessary in order to overcome the problem that frequently arises with relatively taxon-poor pollen spectra, such as those in this study, for which equally close analogues are often located in regions with very disparate climates (Huntley, 1993), leading to potentially very noisy or even quite misleading reconstructions if mean values are taken from analogues that are distributed bimodally with respect to the variable being reconstructed (Haslett et al., 2006). Furthermore, the restriction applied is justified by the palaeovegetation data, including the plant macrofossils recovered from the sediments, that consistently indicate vegetation of an Arctic or Boreal character, and is conservative inasmuch as the threshold chosen corresponds today to the southernmost limit of the Boreal forest zone in southern Fennoscandia (Huntley et al., 1995). Reconstructed values were calculated as inverse distance-weighted means of the 10 closest analogues, chord distance being used to measure analogy and for the distance-weighting. Four variables were reconstructed. Three are bioclimatic variables related to physiological mechanisms by which plant species' distributions are limited (Dahl, 1998), and hence determine vegetation structure and composition: coldest month mean temperature (MTCO, °C); annual temperature sum above 5°C (GDD5, °C days); and annual ratio of actual to potential evapotranspiration (AET/PET – Priestley–Taylor α). The fourth, warmest month mean temperature (MTWA, °C), although less likely to have a mechanistic role in determining either species' distributions in the Arctic or sub-Arctic, or vegetation structure and composition in these regions, was included to provide a basis for comparison with studies reporting mean July temperature reconstructions.

2.5. Time-series analysis

Previous work at over Gunnarsfjorden, using an age–depth model based on fewer ^{14}C age determinations, provided evidence of periodicity in Holocene palaeoclimate and palaeovegetation fluctuations (Allen et al., 2007). We wished to explore whether such periodicity remained apparent when using the new age–depth model for this site, and also whether periodic behaviour was apparent at the other sites. We applied the same approach as Allen *et al*. (2007), using REDFIT v 3.8 (Schulz and Mudelsee, 2002) to perform spectral analyses on data from all three sites. Given information from the Bchron age–depth models about uncertainty in the site chronologies, we also assessed the extent to which the REDFIT results were influenced by this uncertainty. Three spectral analyses were performed for each site using, respectively, each sample's median age and ages corresponding to 2·5% and 97·5% of the range of the probability density function for each sample's age. Spectral analyses were performed on the time series of values for the ratio of abundance of pollen of *Pinus* to that of *Betula*, this ratio having previously been interpreted as an indicator of proximity to a site of the ecotone between *Pinus*-dominated taiga and *Betula*-dominated sub-Arctic woodlands (Allen et al., 2007). Data were de-trended prior to spectral analysis by subtracting a cubic polynomial fitted to the values, analyses being performed on the residuals from the polynomial.

3. Results

3.1. Sites and sampling

3.1.1. liten Čap'pesjav'ri

Coring was carried out at UTM grid reference 35W 04409 78866, 41 m a.s.l., on 28th March 2001. A total sediment depth of 5·25 m was recovered from below a combined ice and water depth of *ca*. 7·0 m. Sediment lithology is summarised in Table S1 (Supplementary Information) and shown on Figure 3.

3.1.2. over Gunnarsfjorden

Coring was performed at UTM grid reference 35W 05424 78821, 78 m a.s.l., on 22nd April 2000. The overall sediment depth recovered was 2·57 m below a combined water and ice depth of *ca*. 4·8 m. Sediment lithology is summarised in Table S2 and shown on Figure 4.

3.1.3. over Kobbkrokvatnet

Cores were collected on 10th April 2001 at UTM grid reference 35W 05847 78455, 51 m a.s.l. Total sediment depth recovered was 5·51 m, the combined ice and water depth being *ca*. 2·3 m. Sediment lithology is summarised in Table S3 and illustrated on Figure 5.

3.2. Chronology

3.2.1. liten Čap’pesjav’ri

AMS ^{14}C age estimates were obtained for 21 samples. Details of materials dated and age estimates obtained are presented in Table S4; the Bchron age–depth model, based upon all 21 age estimates, is shown in Figure 3.

3.2.2. over Gunnarsfjorden

AMS ^{14}C age estimates were obtained for 23 samples. Table S5 presents details of materials dated and age estimates obtained, whilst Figure 4 shows the Bchron age–depth model. The latter is based upon 21 of the age estimates obtained, the lowermost two estimates lying below a substantial hiatus in sediment accumulation and being mutually indistinguishable. One of the 21 age estimates used for the age–depth model was marked as an outlier when constructing the model.

3.2.3. over Kobbkrokvatnet

AMS ^{14}C age estimates were obtained for 20 samples. The materials dated and age estimates obtained are detailed in Table S6, and the Bchron age–depth model illustrated in Figure 5. The age–depth model is based upon all 20 age estimates, although one was marked as an outlier when constructing the model.

3.3. Pollen analysis and palaeovegetation

Together, the pollen percentage (Figures 6 – 8) and pollen accumulation rate (Figures S1 – S3) diagrams from the three sites provide a basis for inferring spatio-temporal patterns in regional vegetation since deglaciation. It also is apparent from comparison of the over Gunnarsfjorden record with those from the other two sites that, as inferred by Allen *et al*. (2007), there is an hiatus at the former site spanning the early Holocene. The moss remains below 207 cm and the discrete moss layer below 215 cm gave ^{14}C age estimates, at 208 cm and 222 cm, that are indistinguishable and that, when calibrated, fall within the Younger Dryas (median calibrated ages: 12,548 and 12,501 cal yr BP respectively; Table S5). In contrast, samples at 200 cm and 197·5 cm gave median calibrated ages of 8794 and 9144 cal yr BP respectively, consistently placing these sediments at an age more than two millennia after the onset of the Holocene.

Examination of the three pollen diagrams leads us to recognise five regional palaeovegetation intervals (RPIs) for northern Finnmark (FM1 – FM5), each spanning around two millennia or more. All exhibit either marked trends or fluctuations during the time spanned. Descriptions of the RPIs are given below.

3.3.1. **RPI FM1** (13,900 – 11,900 cal yr BP)

Pollen of herbaceous taxa dominates the records from all three sites, with *Artemisia* the most abundant taxon in all cases. Chenopodiaceae pollen is also relatively abundant at all three sites, although the other abundant taxa vary between sites. Gramineae and Cyperaceae are markedly more frequent at liten Čap'pesjav'ri, on Magerøya, than at the other two sites, and are least abundant at over Kobbkrokvatnet. This indicates that, whilst the predominant regional vegetation was a dry tundra or steppe–tundra, there was a gradient across the region from relatively moister and perhaps warmer conditions in the west, supporting communities with a higher proportion of graminoids, to drier and probably colder conditions further east where the vegetation was strongly dominated by drought- and/or cold-tolerant *Artemisia*. Marked fluctuations in the relative abundance of various pollen taxa are seen at all three sites during this interval, although their timing generally is difficult to relate to fluctuations recognised elsewhere, for example in the Greenland ice core record (Lowe et al., 2008). At liten Čap'pesjav'ri, however, a sustained reduction in relative abundance of pollen of woody taxa and increase in abundance of *Artemisia* pollen during the last five hundred years of the interval may represent the local expression of the Younger Dryas (GS1, Lowe et al., 2008). The absence of any obvious corresponding fluctuation in relative abundance of pollen of woody taxa at over Kobbkrokvatnet indicates that this fluctuation was not sensed by the vegetation at this eastern site where conditions were very cold and dry throughout this interval.

Pollen accumulation rates and/or concentrations were very low at all three sites throughout this interval, indicating sparse, unproductive vegetation that probably covered only a small fraction of the land surface. Although the earlier part of the interval corresponds to the late-glacial interstadial (GI-1), the relative proximity of all three sites to the northern margin of the Fennoscandian ice sheet and the presence of residual ice cover in the Barents Sea (Lambeck, 1995), as well as the high latitude, likely account for the limited evidence of woody taxa. The only macrofossils recovered from this interval at any of the sites were remains of mosses, a further indication of only sparse presence of vascular plants. Nonetheless, there is a gradient, albeit of small magnitude, in the relative abundance of pollen of woody taxa during the earlier part of this interval, with highest values at the western site that would have been influenced most strongly by meridional penetration of Atlantic waters into the Norwegian Sea during GI-1 (Sarnthein et al., 1995).

3.3.2. **RPI FM2** (11,900 – 10,200 cal yr BP)

This interval was one of transition in the regional vegetation. At liten Čap'pesjav'ri the relative abundance of pollen of woody taxa increased sharply at the onset of this interval. Although subsequently falling back somewhat, a second rise in abundance continued to the end of the interval, by which time values had reached *ca*. 80%. At over Kobbkrokvatnet the increase in relative abundance of pollen of woody taxa was steady throughout the interval, values exceeding 80% by the end of the interval. At both sites *Betula* was the predominant woody taxon during this interval, although *Salix* peaked in abundance during the first half of the interval at both sites. *Betula nana* pollen initially dominated, although *B. pubescens*-type pollen abundance increased throughout, accounting for more than half of the *Betula* pollen towards the end of the interval. At both sites pollen of Ericales peaked in abundance in the latter part of the interval as the abundance of pollen of *Salix* declined. Pollen of *Pinus* was only very sparsely present throughout the interval at over Kobbkrokvatnet, maintaining somewhat higher values at liten Čap'pesjav'ri, although never reaching 10%.

Amongst pollen taxa representing herbaceous plants, *Artemisia* remained prominent at both sites, although at much lower and declining abundances then during the previous interval. Gramineae and Cyperaceae abundances were greater than during the previous interval at over Kobbkrokvatnet, although still less than at liten Čap'pesjav'ri where values were similar to those during FM-1. Other herbaceous taxa probably represent local vegetation patterns, *Rumex/Oxyria* being one of the most abundant at liten Čap'pesjav'ri whereas *Ranunculus*-type was amongst the most abundant at over Kobbkrokvatnet.

Pollen accumulation rates increased during this interval, indicating increasing vegetation cover and productivity. The open unproductive dry tundra or steppe–tundra of the previous interval was replaced by a probably continuous cover of much more productive vegetation of a shrub-tundra character. Initially *Salix* and *Betula nana* were prominent in these communities, although dwarf-shrubs of the Ericales became more important later. Macrofossil evidence from both sites supports the local presence of woody plant taxa, whilst at over Kobbkrokvatnet remains of *Empetrum nigrum*, *Vaccinium myrtillus* and *B. nana* provide insight into the range of dwarf-shrubs present in the shrub tundra communities. The abundance of pollen of *Betula pubescens*-type indicates that stands of *Betula* woodland were present in the region, and perhaps even locally close to the sites, although no macrofossils of tree *Betula* were found from this interval. Woodland stands increased in extent earlier and more rapidly in the west, although subsequently suffering a setback before increasing again later in the interval. This fluctuation may reflect the greater sensitivity of vegetation in the west of the region at this time to varying strength of the meridional flow of Atlantic water into the Norwegian Sea. An early rapid increase in sea surface temperatures near the Faeroes, indicating increased flow of Atlantic water into the Norwegian Sea, is followed by a subsequent decline and then a slower second increase (Rasmussen et al., 2011), although evidence of this fluctuation is not apparent in records from Norwegian coastal waters nor from the western margin of the Barents Sea (Hald et al., 2007). By the end of the interval, *Betula* woodlands were of similar extent and proximity at both the western and eastern sites, although Risebrobakken *et al*. (2010), on the basis of evidence from a core in the south-west Barents Sea, infer that the Polar Front lay to the west of our westernmost site throughout this interval.

3.3.3. **RPI FM3** (10,200 – 8500 cal yr BP)

This interval is characterised by relative pollen abundance of *Betula* reaching its highest values, both at liten Čap’pesjav’ri in the west and at over Kobbkrokvatnet in the east, values in both cases exceeding 60% for part of the interval. At the latter site *B. nana* pollen is predominant, *B. pubescens*-type accounting for only one-quarter to one-third of the *Betula* pollen. Already at the beginning of the interval pollen of *Pinus* is more abundant at both sites than previously, and it increases in abundance throughout. Pollen of Ericales declines in relative abundance during this interval. Pteridophyte spores peak in abundance during this interval, with both *Gymnocarpium dryopteris* especially abundant at over Kobbkrokvatnet and *Lycopodium clavatum* spores abundant at that site and at liten Čap’pesjav’ri. At over Gunnarsfjorden the hiatus in sediment accumulation ended during this interval. A short-lived peak in abundance of pollen of *Betula* follows the renewed onset of sediment accumulation and represents the maximum abundance of this taxon at this site. However, in contrast to the other two sites, this is shortly followed by a sharp increase in abundance of *Pinus* pollen, to values of *ca*. 30%, early in the interval. Such values are never reached during this interval at over Kobbkrokvatnet and are reached only by the end of the interval at liten Čap'pesjav'ri. As at the other two sites, abundance of Pteridophyte spores peaks during this interval.

Pollen accumulation rates increase during this interval at all three sites, indicating further general increase in vegetation productivity and generally more closed vegetation cover. Macrofossil evidence of *Betula pubescens*-type, in the form of fruits and/or leaf fragments, is recorded from all three sites during this interval, indicating the local presence of stands of *Betula* woodlands in addition to the more general expansion of such woodlands across the region. Other taxa found as macrofossils included *Arctostaphylos alpinus*, *Betula nana*, *Empetrum nigrum* and *Vaccinium myrtillus*, reflecting the presence also of a range of shrub-tundra communities. The abundance of Pteridophyte spores, as well as the range of herbaceous taxa that are represented, indicate the presence of either or both of 'meadow' type *Betula* woodlands and forb-dominated herbaceous communities. The vegetation of northernmost Finnmark during this interval apparently exhibited less longitudinal pattern than previously. Forests of *Pinus* were extending closer to the north coast of Finnmark during this interval, however, and were doing so to the greatest extent in central areas. *Pinus* pollen abundance was high at the central site from early in the interval but much lower in the east, where the increase in *Pinus* pollen abundance was most modest. The greater northward extension of *Pinus* in central Finnmark at this time parallels the present situation, with the species reaching its most northerly extent near Børselv (70° 23′ 2·1″ N 25° 43′ 25·1″ E), but extending less far north in the valley of the Tana River to the east (69° 57′ 26·5″ N 26° 37′ 16·1″ E) and having a slightly more southern limit again north of Nieden in Sør Varanger (69° 55′ 47·4″ N 29° 16′ 32·6″ E, BH unpublished data).

Marine records indicate that this was the period of peak warmth during the Holocene, with maximum Atlantic water inflow to the Barents region (Hald et al., 2007) and a more northerly position of the Polar Front than previously, albeit still to the south of its present position (Risebrobakken et al., 2010). The lack of any clear longitudinal gradient in our records is consistent with the inference that the Polar Front continued to lie to the west of all of our sites (Risebrobakken et al., 2010), not even the westernmost of the Finnmark coastal peninsulas coming under the direct influence of Atlantic water at this time.

3.3.4. **RPI FM4** (8500 – 4300 cal yr BP)

This interval is characterised as that during which *Pinus* pollen reaches its highest relative abundance values at both liten Čap'pesjav'ri and over Gunnarsfjorden. Values at both sites are generally > 30% throughout, with peak values > 40%. Values are lower at over Kobbkrokvatnet, being generally > 20% with peaks reaching > 30%, and are not higher overall than during the subsequent interval. At all three sites, however, the pollen accumulation rate, both of *Pinus* and overall, is highest during this interval. The interval also sees higher relative abundance and accumulation rate values than previously for *Alnus* and *Juniperus* and consistent occurrence of *Ulmus* pollen at all three sites. Ericales pollen increases in relative abundance after *ca*. 6500 cal yr BP at all three sites, Gramineae pollen showing a complementary decrease. *Filipendula* pollen is consistently present before this date at liten Čap'pesjav'ri and over Gunnarsfjorden but much sparser in occurrence thereafter; at over Kobbkrokvatnet, however, the decrease in this taxon in the second part of the interval is less marked.

Macrofossil evidence of *Betula pubescens*-type from this interval at both liten Čap'pesjav'ri and over Kobbkrokvatnet indicates the continued local presence of *Betula* woodlands. *Juniperus* needles recovered from the sediments at over Gunnarsfjorden indicate that this shrub also was locally present. Macrofossils of dwarf shrubs also were found, including *Empetrum nigrum* and *Vaccinium myrtillus*, as well as of Cyperaceae. The absence of any macrofossil evidence of *Pinus* is taken to indicate that this tree was not locally present but rather that the increased pollen accumulation rates indicate closer proximity of the ecotone between the *Betula* woodlands and the *Pinus* taiga to the south (Allen et al., 2007). The greater abundance of pollen of Gramineae and *Filipendula* earlier in the interval, but of Ericales later, may indicate a shift from 'meadow' to 'heath' type *Betula* woodlands, or the replacement of *Betula* woodlands by shrub-tundra, after *ca*. 6500 cal yr BP. At liten Čap'pesjav'ri and over Kobbkrokvatnet this shift corresponds to a marked reduction in the proportion of *Betula pubescens*-type pollen and to a preponderance of *B. nana* pollen, suggesting that the latter inference, namely a reduction in the local extent or occurrence of *Betula* woodlands, is most likely to account for the other changes recorded.

The association of higher relative abundances of pollen of *Alnus* and *Juniperus*, and of consistent presence of *Ulmus*, with this interval of highest accumulation rates of *Pinus* pollen indicates that climatic conditions during this interval were generally warmer than previously, enabling all of these trees and shrubs to extend their ranges closer to, or into, northernmost Finnmark. However, the interval also is characterised by fluctuations in the relative abundance of pollen of *Pinus* and *Betula* (Figure 9) at all three sites. Following Allen *et al*. (2007) we interpret these fluctuations as indicating shifts in the latitudinal position of the *Pinus–Betula* ecotone, with higher values of the *Pinus:Betula* pollen abundance ratio indicating more northerly positions and *vice versa*. The chronological uncertainties render difficult a simple visual comparison of the records for this ratio from the three sites; we therefore identified peaks in each record and used Bchron (Parnell et al., 2008) to assess the probability that given peaks in the three records were not synchronous. Five of the most prominent peaks, centred on (a) *ca*. 8375 (95 % ranges 8150–8475, 8000–8500 and 8375–8725 at liten Čap'pesjav'ri, over Gunnarsfjorden and over Kobbkrokvatnet respectively), (b) *ca*. 7700 (95 % ranges 7500–7800, 7300–8250 and 7425–7650), (c) *ca*. 6450 (95 % ranges 6200–6550, 6150–6750 and 6200–6750), (d) *ca*. 5675 (95 % ranges 5450–5850, 5475–5875 and 5600–5850) and (e) *ca*. 4525 (95 % ranges 4300–4675, 4350–4750 and 4100–4750) cal yr BP (a – e correspond to peak labels on Figure 9) were identified in all three records and had indistinguishable ages at the three sites. These peaks generally are much more muted at over Kobbkrokvatnet than at the other two sites. Three others, centred on *ca*. 7000 (f), *ca*. 6725 (g) and *ca*. 5125 cal yr BP (h), were identified only at liten Čap'pesjav'ri and over Gunnarsfjorden, with indistinguishable ages at these sites. Most peaks identified at both liten Čap'pesjav'ri and over Gunnarsfjorden are stronger at liten Čap'pesjav'ri (b, g, c and e) or of similar strength at the two sites (a and h), only a minority being stronger at over Gunnarsfjorden (f and d). A minority of peaks could be identified only in the record from over Gunnarsfjorden (i: *ca*. 7375; j: *ca*. 6275; and k: *ca*. 5350 cal yr BP); this probably reflects the higher temporal resolution of this record rather than greater sensitivity at this site. Northward excursions of the latitudinal position of the *Pinus–Betula* ecotone, and hence its greater proximity to the sites studied, apparently were thus both of greater magnitude and more frequent in western Finnmark than in the east.

3.3.5. **RPI FM5** (4300 cal yr BP to present)

This final interval, that extends to the present day, has lower relative abundance and pollen accumulation rates of *Pinus* than the preceding interval, values being *ca*. 20 – 30% at all three sites. Whereas *Pinus* pollen relative abundance falls at the outset of the interval at liten Čap'pesjav'ri, the decrease at over

Gunnarsfjorden is delayed by *ca*. 550 yr to *ca*. 3750 cal yr BP. This mirrors the earlier increase in relative abundance at this site that occurs *ca*. 750 yr earlier than at liten Čap'pesjav'ri, at *ca*. 9250 cal yr BP, during RPI FM3. Although *Pinus* pollen accumulation rate falls at over Kobbkrokvatnet, relative abundance values are similar to those during the previous interval. Relative abundance values of *Betula* pollen are similar to those during the previous interval, but those for *Alnus* decrease and pollen of *Ulmus* is only intermittently present. *Picea* pollen, in contrast, is now recorded consistently at all three sites, most probably reflecting the increasing range and abundance of this taxon in the taiga to the south rather than its presence in Finnmark, the whole of which lies north of the present range of *P. abies*. Ericales pollen increases in relative abundance, especially at liten Čap'pesjav'ri, and *Empetrum* pollen also is now consistently recorded at all three sites. The proportion of *Betula pubescens*-type pollen continues to be low at liten Čap'pesjav'ri and over Kobbkrokvatnet, with *B. nana* accounting for the majority of the *Betula* pollen recorded. There is a general trend of increase in pollen of herbaceous taxa relative to woody taxa, although pollen accumulation rates for herbaceous taxa decrease overall; a few taxa, however (e.g. *Rumex/Oxyria* and *Thalictrum* at over Gunnarsfjorden), show increased pollen accumulation rates.

Macrofossil evidence from this interval is principally of dwarf shrubs, including *Betula nana*, *Empetrum nigrum*, *Vaccinium myrtillus* and *V. vitis-idaea*. Remains are also present of herbaceous taxa, including Cyperaceae and *Ranunculus*, and of *Betula pubescens*-type, although the latter was recorded only at over Kobbkrokvatnet. Shrub-tundra communities dominated during this interval, along with some herbaceous communities of a mesic nature. *Betula* woodlands were more localised and decreased in the far north, with persistence today only of isolated relict stands such as that at Oksefjorden; the treeline generally retreated southwards to occupy a position similar to that at present (Figure 1). The generally lower abundance of *Pinus* pollen than previously indicates a parallel southward retreat of the *Pinus–Betula* ecotone. The *Pinus:Betula* pollen abundance ratio at all three sites is similar during this interval, values generally being in the range seen at over Kobbkrokvatnet during RPI FM4, and shows smaller amplitude fluctuations than during the previous interval. Evidence of coincident fluctuations is less clear than earlier, although two peaks with ages that do not differ significantly between sites are apparent in all three records (m: *ca*. 1775; and o: *ca*. 1025 cal yr BP) and another in the records from liten Čap'pesjav'ri and over Kobbkrokvatnet (n: *ca*. 3250 cal yr BP). All three sites show lower values of the ratio between *ca*. 2450 and 2150 cal yr BP and again between *ca*. 1400 and 1100 cal yr BP, and higher values between *ca*. 2050 and 1550 cal yr BP. Interestingly, these coincident fluctuations parallel evidence for variation in IRD inputs and salinity from marine core PSh-5159N (Risebrobakken et al., 2010), episodes of increased IRD input and reduced salinity coinciding with lower values of the *Pinus*:*Betula* ratio at all three sites. These episodes of lower salinity and increased IRD input are interpreted as evidence of increased influence of coastal water and greater extent and/or frequency of winter sea-ice along the Finnmark coast (Risebrobakken et al., 2010), consistent with the generally cooler conditions inferred from the lower *Pinus*:*Betula* ratio. The most prominent peaks in the ratio are at over Gunnarsfjorden (l: *ca*. 3800 cal yr BP; and m), with smaller peaks at liten Čap'pesjav'ri (n, m and o), over Gunnarsfjorden (p: 675 cal yr BP; and o) and over Kobbkrokvatnet (q: *ca*. 2550 cal yr BP). The ratio shows a decrease over the last three centuries or so at all three sites, although with evidence of increase again since *ca*. 125 cal yr BP in the higher temporal resolution record from over Gunnarsfjorden that may indicate recent northward advance of the *Pinus*–*Betula* ecotone in response to climatic warming over the same period (Trenberth et al., 2007).

3.4. Palaeoclimate reconstructions

Holocene palaeoclimate reconstructions are shown in Figure 10. Mean standard errors of the reconstructions are presented in Table 2; they were in all cases relatively small, as were the mean chord distances. Mean reconstructed values for RPIs FM2 – FM5 at each site are presented in Table 3. Reconstructions are not presented for late-glacial parts of the liten Cap'pesjav'ri and over Kobbkrokvatnet records, nor for samples from below the inferred hiatus at over Gunnarsfjorden, because the analogues were poor and reconstructed values, as a result, unreliable. This is a frequently encountered problem when, as here, pollen spectra are dominated by a limited number of herbaceous taxa, notably *Artemisia*, Chenopodiaceae and Gramineae. Equally close potential analogues for such spectra often can be found in areas of high latitude tundra and of mid-continental steppe. Such regions, however, have very different climates, leading to bimodal distributions of climatic variable values amongst the 10 closest analogues (Haslett et al., 2006) and hence misleading or even meaningless weighted mean values.

The first reconstructions considered potentially reliable thus come from RPI FM2. Annual thermal sum was markedly lower than at present, by *ca*. 100 – 160 °C days, at both sites. Coldest month mean temperature was also lower, although to a much greater extent in the west, at liten Cap'pesjav'ri, than in the east, at over Kobbkrokvatnet, values being 8·3°C and 1·7°C cooler respectively. Warmest month mean temperature was much less reduced and showed the opposite spatial pattern, being 1·1°C cooler in the west and 1·9°C cooler in the east. Moisture availability was also reduced at both sites.

The onset of FM3 was associated with an increase in annual thermal sum to values close to or exceeding present values at all three sites. Coldest month mean temperature also increased in the west but decreased in the east, resulting in a similar pattern to present, with lower values in the east, although with a gradient only half that at present. Values remained markedly lower than at present, by between 3·7°C, in the east, and 5·1°C, in the west. Warmest month mean temperatures increased too, reaching values up to 1·6°C warmer than at present. Moisture availability increased, with no deficiency at liten Cap'pesjav'ri or over Gunnarsfjorden and only marginal deficiency at over Kobbkrokvatnet, the eastern site.

Marked fluctuations in reconstructed values characterise FM4, reflecting the marked fluctuations in relative abundance of pollen of *Pinus* during this interval. Mean annual thermal sum was higher than at present at all three sites, by between 61 and 200 °C days, the greatest mean increase being at over Gunnarsfjorden. However, values varied over a range of 202 – 390 °C days during this interval, the smallest range (202 °C days) and lowest maximum (613 °C days) being at over Kobbkrokvatnet and the largest range (390 °C days) and highest maximum (763 °C days) being at liten Cap'pesjav'ri. Coldest month mean temperatures were warmer than during the previous interval, by between 0·7°C and 1·2°C, but still cooler than present, by between 2·9°C, in the east, and 3·9°C, in the west; they too varied markedly during this interval at all three sites, although most strikingly at over Gunnarsfjorden. Warmest month mean temperatures were also warmer than previously, by between 0·4°C and 0·6°C, exceeding present values by between 0·7°C and 2·2°C, but had a smaller amplitude of variation than coldest month temperatures. Moisture deficiency was absent or no more than marginal during this interval.

The transition to FM5 was marked by a decrease in annual thermal sum at all three sites, by between 52 and 107 °C days, values being close to or somewhat above present values. Coldest month mean temperature increased, by between 0·9°C and 2·1°C, although mean values remained 1·5 – 3·0°C cooler than present, with the coolest absolute value at the eastern site but the greatest difference from the present value at the western site. Warmest month mean temperatures were cooler than previously, although only by between 0·6°C and 1·1°C, and close to present values, from which they differed by between 0·1°C and 1·1°C. No moisture deficiency occurred at any of the sites.

3.5. Time-series analysis

The results of the time-series analyses for the three sites are summarised in Table 4. Although none of the spectral peaks exceeded the 99% level, a number exceeded the 95% level and others the 90% level. Strikingly, several periodicities were consistently identified both using the three different chronologies for a single site and at different sites. The most strongly supported periodicities were of 1265 – 1380 yr, exceeding the 95% level for two chronologies at over Gunnarsfjorden and the 90% level for the third chronology at this site and two of the chronologies at over Kobbkrokvatnet, and of 931 – 1012 yr, exceeding the 95% level for all three chronologies at over Gunnarsfjorden and the 90% level for two of the chronologies at over Kobbkrokvatnet. The latter periodicity most likely reflects the 950 yr Suess cycle of solar variability. Although neither periodicity was identified at liten Cap'pesjav'ri, a periodicity of 631 – 675 yr that exceeded the 95% level for two chronologies at that site, and the 90% level for the third chronology, as well as for two chronologies at over Gunnarsfjorden, may represent an harmonic of the 1265 – 1380 yr periodicity. A periodicity of 561 – 598 yr exceeded the 95% level for the median chronology at over Gunnarsfjorden and the 90% level for two chronologies at over Kobbkrokvatnet; although this may be an harmonic of the *ca*. 1800 yr tidal cycle that relates to lunar orbital periodicity (Derop, 1971; Keeling and Whorf, 2000) and that has previously been detected in a marine sediment record close to the Antarctic Peninsula (Warner and Domack, 2002), the mechanism that might generate such an harmonic is unclear. A periodicity of 321 – 357 yr, however, that exceeded the 90% level for two chronologies at over Gunnarsfjorden and one at over Kobbkrokvatnet, may reflect the *ca*. 360 yr tidal cycle (Keeling and Whorf, 2000). A further periodicity of 253 – 263 yr exceeded the 95% level for one and the 90% level for the other two chronologies at the former site; it may be an harmonic of the 931 – 1012 yr periodicity. Other shorter periodicities are also detected at over Gunnarsfjorden, where the sample resolution is higher. One of 209 – 212 yr that exceeded the 90% level for two chronologies may reflect the 210 yr de Vries cycle of solar activity, whilst that of 190 yr that exceeded the 95% level for one chronology at over Gunnarsfjorden may reflect the *ca*. 180 yr tidal cycle (Keeling and Whorf, 2000). Longer periodicities, of 1474 yr and 1694 yr, exceeded the 90% level for one chronology each at over

Kobbkrokvatnet and over Gunnarsfjorden respectively; at least the longer of these may represent a manifestation of the *ca*. 1800 yr tidal cycle, the period of which is at times as short as 1682 yr (Keeling and Whorf, 2000).

These results provide support for periodicity of Holocene climate and vegetation fluctuations across the region, especially at millennial and somewhat longer than millennial frequencies. One of the two periodicities receiving strongest support (1265 – 1380 yr) may correspond to the cycle of 1470 ± 585 yr identified for petrological tracers in North Atlantic sediments (Bond et al., 2001; Bond et al., 1997) and the *ca*. 1500 yr cycle in inferred south-westerly deep water flow south of Iceland (Bianchi and McCave, 1999). Although this periodicity is not detected at the western site, a shorter periodicity (631 – 675 yr) that is detected there is most probably an harmonic of the longer periodicity, perhaps suggesting that this harmonic and the main periodicity have more similar strength at this locality than at the central site.

4. Discussion

The results presented above provide evidence supporting our primary hypothesis, that the Holocene palaeovegetation and palaeoclimatic fluctuations and trends reported by Allen *et al*. (2007) are regional phenomena, and thus are recorded also elsewhere in Finnmark. In addition, these results support our secondary hypothesis, that the expression of these fluctuations varies systematically with longitude; this, in turn, supports the underlying hypothesis, that these fluctuations principally reflect variations in strength of the warm surface NCaC that are associated with millennial variations in strength of the AMOC. Our palaeovegetation and palaeoenvironmental inferences are summarised in Table 5.

Following deglaciation, during the late-glacial 13,900 – 11,900 cal yr BP (RPI FM1), the vegetation of northern Finnmark was unproductive and sparse, with herbaceous taxa tolerant of cold dry conditions predominating in the pollen record. Birks *et al*. (2012) report similar evidence from the site of Jansvatnet, near Hammerfest in western Finnmark, *ca*. 80 km to the south-west of liten Čap'pesjav'ri. Interestingly, they record relatively abundant pollen of Gramineae and maximum relative abundance values of *Artemisia* pollen of *ca*. 35%. This is consistent with the gradient in our palaeovegetation records for this time, relative abundance values of Gramineae decreasing eastwards whereas those of *Artemisia* increase eastwards. Although we were unable to obtain reliable palaeoclimatic reconstructions for this initial interval, this gradient suggests relatively moister, and perhaps also warmer, conditions in the west, and drier, probably colder, conditions in the east. The very low pollen accumulation rates, the nature of the sediments and the predominance of herbaceous pollen taxa all indicate, as Birks *et al*. (2012) infer, that the regional vegetation was analogous to polar desert during the period immediately following deglaciation and during much of the late-glacial period. Generally higher relative abundance of pollen of *Betula nana* and of *Salix* at liten Čap'pesjav'ri than at our two other sites, however, likely indicates the presence of areas of shrub-tundra, further indicating moister conditions in the west. This inference is consistent with penetration of warmer Atlantic surface waters into the Norwegian Sea during the late glacial. Rapid fluctuations in the proportions of pollen of woody *versus* herbaceous taxa at liten Čap'pesjav'ri during this period probably indicate fluctuations in the extent of such penetration, whilst the generally much lower proportion of pollen of woody taxa and more progressive changes seen at over Kobbkrokvatnet indicate warm water did not extend around the Finnmark coast as far as Varangerhalvøya. The two samples from the latter site showing much higher relative abundance of pollen of woody taxa had very low pollen concentrations and extremely low pollen counts; they are thus not considered reliable.

RPI FM2 (11,900 – 10,200 cal yr BP) represents the end of the Younger Dryas and the first millennium or so of the Holocene. During this time the record from liten Čap'pesjav'ri continues to exhibit greater sensitivity than that from over Kobbkrokvatnet, suggesting that warm surface water penetration, and especially fluctuations in the strength of this circulation, continued to influence western Finnmark much more strongly. The record from Lake Ifjord (Seppä et al., 2002) provides support for this conclusion, showing more subdued fluctuations than those seen at liten Čap'pesjav'ri, albeit with more evidence of fluctuations than at over Kobbkrokvatnet. Climatic conditions were markedly cooler than present, with some degree of moisture deficiency. Strikingly, the palaeoclimatic reconstructions suggest that winter temperatures were more severe in the west, in contrast to summer temperatures and annual thermal sum that were lower in the east; moisture deficiency was also greater in the west. This apparent conflict with the evidence that warm surface waters in the Norwegian Sea influenced principally the west of Finnmark may be explained by extensive winter sea ice blocking any influence of Atlantic surface waters during that season. Pollen accumulation rates continued to be very low, indicating that the vegetation cover continued to be very sparse, although somewhat higher values in the west are consistent with the west–east gradient in thermal sum.

RPI FM3 (10,200 – 8500 cal yr BP) saw the principal early-Holocene transition in regional vegetation and climate, with pollen accumulation rates increasing markedly and the relative abundance of pollen of *Pinus* also increasing. Annual thermal sum and warmest month mean temperatures reached or exceeded present values, although coldest month mean temperatures remained cooler than present. The present west–east gradient in climatic conditions was by this time clearly established. Peak relative abundance of pollen of *Betula* is reached during this interval, and the presence of macrofossils of *Betula pubescens*-type at all three sites attests to the rapid expansion of *Betula* woodlands throughout the region, the treeline extending generally to higher latitudes than at present. Fluctuations in the relative abundance of pollen of *Betula nana*, however, indicate that climatic conditions did not change smoothly during this interval. Coincident peaks in *B. nana* pollen at liten Čap'pesjav'ri and at over Kobbkrokvatnet at *ca*. 9500 – 9600 cal yr BP and at *ca*. 8900 cal yr BP indicate regional cooling events. These are much more strongly expressed at the former site, where *Betula pubescens*-type pollen abundance is much higher overall, suggesting that they reflect weakening of the NCaC, penetration of which was barely reaching eastern Finnmark even when the flow was stronger.

Pollen accumulation rates, and the overall relative abundance of pollen of *Pinus*, were at their maximum 8500 – 4300 cal yr BP (RPI FM4). Annual thermal sum and warmest month mean temperatures were higher than previously and both exceeded present values. Coldest month mean temperatures, although warmer than previously, were still below present values. The most striking feature of this interval, however, is the frequent fluctuations in both the palaeovegetation record and the reconstructed climatic conditions. Although five peaks in the *Pinus:Betula* ratio are seen at all three sites, they are generally least strongly expressed at over Kobbkrokvatnet and most marked in the record from liten Čap'pesjav'ri; three further peaks are recorded at liten Čap'pesjav'ri and over Gunnarsfjorden that are not apparent at over Kobbkrokvatnet. The majority of those peaks recorded at the latter two sites are more strongly expressed at liten Čap'pesjav'ri or of similar magnitude at the two sites. At over Gunnarsfjorden a marked minimum in the ratio at *ca*. 8225 cal yr BP is likely to represent the local expression of the 8·2 kyr event (Allen et al., 2007; Alley et al., 1997). Although minima in the ratio are not so clearly seen at the other two sites, all three show minima in the reconstructed annual thermal sum that likely reflect this cold event: minimum values of GDD5 are reconstructed at *ca*. 8330 cal yr BP at liten Čap'pesjav'ri, at *ca*. 8320 cal yr BP at over Gunnarsfjorden and at *ca*. 8350 cal yr BP at over Kobbkrokvatnet. A picture thus emerges of fluctuations in temperature that most probably reflect variations in the amount of thermal energy transported to the region by ocean circulation. This might result either from variations in the strength and eastward penetration of the NCaC, and hence in the volume of Atlantic water transported around Nordkapp, from variations in the temperature of Atlantic water reaching the Barents Sea, and/or from variations in the strength of the Greenland anticyclone, and hence in the amount of sea ice transported to the southern Barents Sea (Risebrobakken et al., 2010). Whichever of these potential mechanisms was of greatest importance, at *ca*. 8400, 7600, 6400, 5600 and 4500 cal yr BP the entire regional climate was influenced by warming, whereas at *ca*. 6950, 6725 and 5100 cal yr BP easternmost parts of the region were uninfluenced. It is more difficult to account for those cases when over Kobbkrokvatnet was uninfluenced whilst the peak in the *Pinus*:*Betula* ratio was similar in magnitude at the other two sites, or even of greater magnitude at over Gunnarsfjorden, as happened at *ca*. 6950 and 5100 cal. yr BP. One possibility, however, is that whilst the volume and penetration of the NCaC was less at these times than when the entire region was affected, the temperature of the water in the NCaC, and hence the energy transported, was greater at these times.

Although the *Betula* treeline during FM4 was still sufficiently far north of its present position to encompass all three sites, the *Pinus*–*Betula* ecotone was generally much closer to the western and central sites than to the eastern site. This implies a stronger southward decrease in the latitude of this ecotone with increasing longitude than at the present; in turn, this most likely implies a similar shift in the pattern of annual thermal sum. The earlier increase and later decrease in relative abundance of *Pinus* pollen at over Gunnarsfjorden suggest that the ecotone shifted northwards first in the centre of the region, and also persisted in a more northerly position longest there.

Accumulation rate and relative abundance of *Pinus* pollen were both lower during the final RPI FM5 (4300 cal yr BP to present), although the latter was less marked at over Kobbkrokvatnet where *Pinus* values were generally lower throughout than at the other two sites. Climatic conditions generally approached those of the present, although coldest month mean temperatures remained generally below present. Our evidence indicates that climatic fluctuations were generally of smaller magnitude than previously, although they continued to occur. Although this appears to contrast with marine evidence that is inferred to indicate increased instability of conditions in the Barents Sea region since *ca*. 2500 cal yr BP (Risebrobakken et al., 2010), it may be that the latter instability, recorded in core PSh-5159N taken to the west of our region of study, did not extend eastwards sufficiently to affect most of coastal Finnmark. The *Pinus–Betula* ecotone and the *Betula* treeline both generally retreated southwards during this time, all three sites now being beyond treeline. Relict stands of *Betula* woodland and *Pinus* forest north of the present general treeline and ecotone respectively probably became isolated during this time. These southward retreats are consistent not only with our inference of cooler growing season conditions than during the earlier Holocene, but also with the interpretation proposed by Risebrobakken *et al*. (2010) who suggest an increase in the area influenced by coastal water, more sea ice and predominantly cold conditions associated with weaker south-westerly winds after *ca*. 2500 cal yr BP.

Our results and conclusions are thus generally consistent with recent evidence from marine sediment cores in the Barents Sea (Slubowska-Woldengen et al., 2008) and with linked sediment-based and modelling studies (Risebrobakken et al., 2011) of ocean conditions in the region. Whilst the marked fluctuations that we record during FM4 are not consistently seen in records from the ocean realm (although see Hald et al., 2007), this may reflect the location of available records in relation to the complexities of Holocene changes in ocean circulation and conditions in the Barents Sea region. The recent modelling study by Semenov *et al*. (2009), however, offers the intriguing possibility that the phenomena recorded by our palaeovegetation studies reflect periodic shut downs of the Barents Sea inflow triggered by solar variability through a feedback mechanism mediated by sea-ice formation. Evidence of periodicity of these fluctuations in our records, and apparent coincidence between some of the frequencies detected and those of known periodic variations in solar output, adds weight to this hypothesis. Testing this hypothesis as to the mechanism, however, will require records from ocean sediment cores with both high resolution and, most importantly, comparably precise chronologies to those obtained for the sites we present here.

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Tables

Table 1: Present climate of the sites investigated

Site	**MTCO** (°C)	**MTWA** (°C)	**GDD0** (°C day)	**GDD5** (°C day)	**WINPPT** (mm)	**SUMPPT** (mm)	**ANNPPT** (mm)	**AET/PET**
liten Cap'pesjav'ri	–3·6	11·2	1317	478	362	251	613	1·0
over Gunnarsfjorden	–5·4	9·5	1058	314	245	226	471	1·0
over Kobbkrokvatnet	–6·5	10·5	1198	424	251	248	499	1·0

MTCO – coldest month mean temperature; MTWA – warmest month mean temperature; GDD0 – annual temperature sum above a 0°C threshold; GDD5 – annual temperature sum above a 5°C threshold; WINPPT – winter (October – March) precipitation; SUMPPT – summer (April – September) precipitation; ANNPPT – annual precipitation; AET/PET – Priestley–Taylor α index of moisture availability. All values are 30-year (1961 – 90) means interpolated for the site locations (defined by their longitude, latitude and altitude) using the Laplacian thin-plate splines method of Hutchinson (1989) applied to a compilation of meteorological station data (Leemans and Cramer, 1991 with additional data compiled by W. Cramer).

Table 2: Mean standard errors and chord distances for palaeoclimate reconstructions

Site	**Chord distance**	**MTCO** (°C)	**MTWA** (°C)	**GDD5** (°C days)	**AET/PET**
liten Cap'pesjav'ri	0·073	1·05	0·48	55·0	0·0021
over Gunnarsfjorden	0·065	0·82	0·40	42·7	0·0005
over Kobbkrokvatnet	0·056	0·95	0·40	43·3	0·0018

Table 3: Mean reconstructed climatic conditions for each Regional Palaeovegetation Interval (RPI) at each site

RPI	Site	MTCO (°C)	MTWA (°C)	GDD5 (°C days)	AET/PET
FM2	liten Cap'pesjav'ri	-11·9	10·1	375	0·969
	over Gunnarsfjorden	–	–	–	–
	over Kobbkrokvatnet	-8·2	8·6	258	0·980
FM3	liten Cap'pesjav'ri	-8·7	11·3	429	1·000
	over Gunnarsfjorden	-9·7	11·1	425	1·000
	over Kobbkrokvatnet	-10·2	11·4	434	0·991
FM4	liten Cap'pesjav'ri	-7·5	11·9	551	1·000
	over Gunnarsfjorden	-9·0	11·7	514	0·998
	over Kobbkrokvatnet	-9·4	11·8	485	1·000
FM5	liten Cap'pesjav'ri	-6·6	11·3	483	1·000
	over Gunnarsfjorden	-6·9	10·6	407	1·000
	over Kobbkrokvatnet	-8·4	11·1	433	1·000

Table 4: Time-series analysis results

Bchron chronology (cumulative % of pdf)		**2·5%**	**50·0%**	**97·5%**
Site	**Mean sample interval** (yr ± sd)	**Periodicities detected** (yr)		
liten Cap'pesjav'ri	195 ± 66	634[c]	***645***[c]	***631***[c]
over Gunnarsfjorden	88 ± 51	1694 ***1331***[a] ***931***[b] 259[f] 212[g] 198 ***190***	1280[a] ***960***[b] 640[c] ***582***[d] 349[e] 253[f]	***1265***[a] ***1012***[b] 675[c] 321[e] ***263***[f] 209[g]
over Kobbkrokvatnet	198 ± 130	1474 598[d] 357[e]	1380[a] 978[b] 460 405	1309[a], 981[b] 561[d]

Periodicities shown in ***bold-italic*** exceeded the 95% level; the remainder exceeded the 90% level. Superscripts are used to indicate periodicities for different sites and/or chronologies that are considered equivalent.

Table 5: Summary of palaeovegetation and palaeoenvironmental inferences

<table>
<tr><th rowspan="2">RPI</th><th colspan="3">West -- > East</th></tr>
<tr><th>liten Čap’pesjav’ri</th><th>over Gunnarsfjorden</th><th>over Kobbkrokvatnet</th></tr>
<tr><td rowspan="5">FM1</td><td colspan="3">unproductive, sparse vegetation of herbaceous taxa – analogous to polar desert</td></tr>
<tr><td>Gramineae more abundant; decreasing eastwards</td><td></td><td>Artemisia more abundant; decreasing westwards</td></tr>
<tr><td>dwarf-shrub taxa more abundant than to the east</td><td></td><td></td></tr>
<tr><td>warmer, moister conditions</td><td></td><td>colder, drier conditions</td></tr>
<tr><td>fluctuating proportions of woody vs herbaceous taxa indicating fluctuating influence of warmer waters that reached the Norwegian Sea</td><td></td><td>lower proportion of woody taxa with progressive changes indicating little or no influence of warmer waters that reached the Norwegian Sea</td></tr>
<tr><td rowspan="5">FM2</td><td colspan="3">Sparse vegetation dominated by herbaceous taxa</td></tr>
<tr><td>higher pollen accumulation rates; more productive vegetation</td><td></td><td>lower pollen accumulation rates; less productive vegetation</td></tr>
<tr><td colspan="3">much cooler than present all year round; some moisture deficiency</td></tr>
<tr><td>colder winters, higher annual thermal sum and drier in the west</td><td></td><td></td></tr>
<tr><td>more fluctuating conditions</td><td></td><td>more stable conditions</td></tr>
<tr><td rowspan="4">FM3</td><td colspan="3">shrub tundra predominant with scattered Betula woodlands</td></tr>
<tr><td>Betula pubescens-type pollen more abundant in the west indicating more extensive woodland cover than to the east</td><td></td><td></td></tr>
<tr><td colspan="3">annual thermal sum and warmest month temperatures as high or higher than present;
winter conditions remain cooler than present</td></tr>
<tr><td>regional cooling events, reflected by peaks in abundance of Betula nana pollen, expressed more strongly in the west</td><td></td><td></td></tr>
<tr><td rowspan="5">FM4</td><td colspan="3">shrub tundra with stands of Betula woodland; Pinus–Betula ecotone at its closest
frequent large magnitude fluctuations in the relative abundances of Pinus and Betula</td></tr>
<tr><td colspan="3">Pinus–Betula ecotone at higher latitude in the west and centre, further south in the east</td></tr>
<tr><td></td><td>Pinus extended northwards earlier and persisted later, in central areas</td><td></td></tr>
<tr><td>fluctuations more numerous and generally strongest in the west, indicating stronger influence of Atlantic waters on climate in the west</td><td></td><td>fewer fluctuations of smaller magnitude in the east; Pinus abundance generally lower in the east</td></tr>
<tr><td colspan="3">annual thermal sum and warmest month temperatures maximal and higher than present;
winter conditions cooler than present;
frequent large magnitude fluctuations in annual thermal sum</td></tr>
<tr><td rowspan="4">FM5</td><td colspan="3">shrub tundra dominant; Betula woodlands more localised and of decreased extent;
Pinus–Betula ecotone and treeline more southerly in position than previously;
fluctuations in relative abundances of Pinus and Betula less marked than previously</td></tr>
<tr><td>Pinus abundance and magnitude of fluctuations greater in west and centre</td><td></td><td>Pinus abundance and magnitude of fluctuations much less in the east</td></tr>
<tr><td colspan="3">climatic conditions generally approaching current conditions, although winters cooler;
climatic fluctuations of smaller magnitude than previously</td></tr>
<tr><td>magnitude of climatic fluctuations greater in the west and centre</td><td></td><td>climatic fluctuations of lesser magnitude in the east</td></tr>
</table>

Figure captions

Figure 1: Location of the study area and sites sampled

(a) Shows the location of the study area in northern Norway and how it is related to the principal present ocean surface currents. (b) Shows the locations of the three sites examined in relation to a schematic representation of the present major vegetation patterns, previously studied sites and principal settlements.

Figure 2: Local topographic maps for the sites sampled

Maps showing locations and local topographic settings of: (a) liten Čap'pesjav'ri; (b) over Gunnarsfjorden; and (c) over Kobbkrokvatnet. Re-drawn from 1:50,000 topographic maps (Topografisk Hovedkartserie—M711, Blad 2037 II 'Nordkapp', Blad 2237 II 'Mehamn' and Blad 2336 II 'Kongsfjord', respectively; Statens Kartverk, N–3500 Hønefoss).

Figure 3: Age–depth model and lithology for liten Čap'pesjav'ri

Figure 4: Age–depth model and lithology for over Gunnarsfjorden

Figure 5: Age–depth model and lithology for over Kobbkrokvatnet

Figure 6: Pollen percentage diagram for liten Čap'pesjav'ri

Figure 7: Pollen percentage diagram for over Gunnarsfjorden

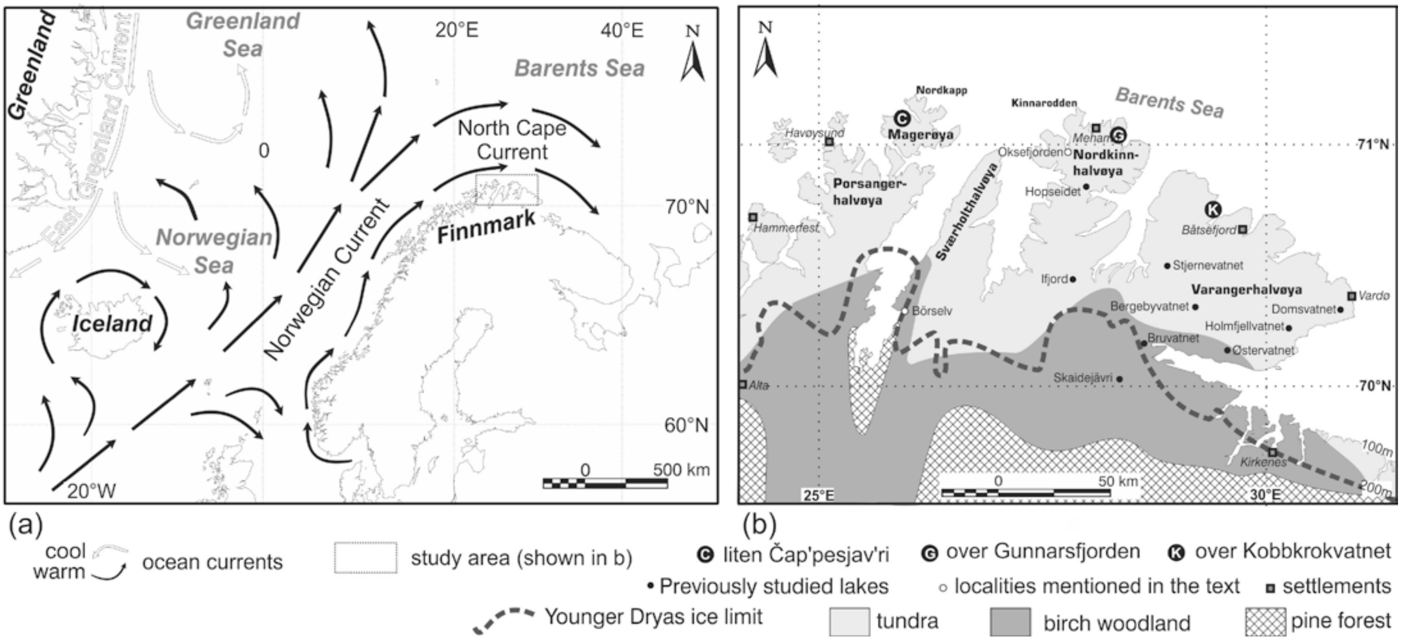
Figure 8: Pollen percentage diagram for over Kobbkrokvatnet

Figure 9: *Pinus:Betula* pollen abundance ratios

Pinus:*Betula* pollen abundance ratios for the three sites plotted against their median, 2·5 % and 97·5 % chronologies derived from Bchron (Parnell et al., 2008), illustrating the 95 % confidence range for the ages associated with fluctuations in the ratio. Peaks labeled a – q are those referred to in the text, peaks interpreted as coincident in two or more sites being indicated by the same letter.

Figure 10: Palaeoclimate reconstructions

Reconstructed values for coldest and warmest month mean temperatures (MTCO and MTWA) and annual thermal sum above 5°C (GDD5) (a – c), and for annual ratio of actual to potential evapotranspiration (AET/PET) (d – f), for liten Čap'pesjav'ri (a and d), over Gunnarsfjorden (b and e) and over Kobbkrokvatnet (c and f). Vertical dotted lines indicate boundaries between regional palaeovegetation intervals.



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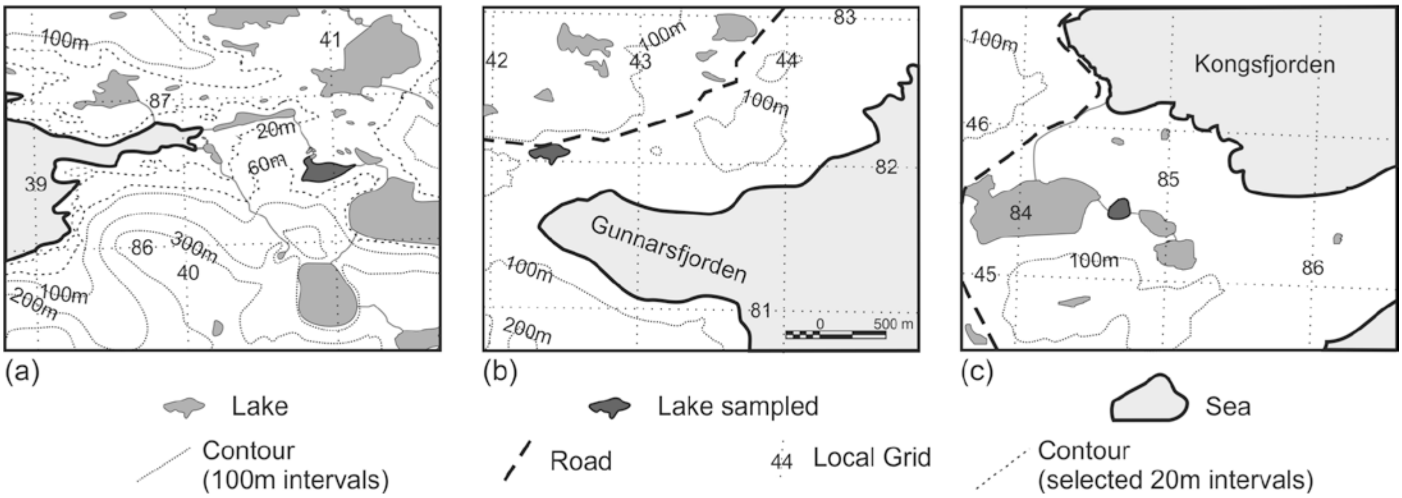

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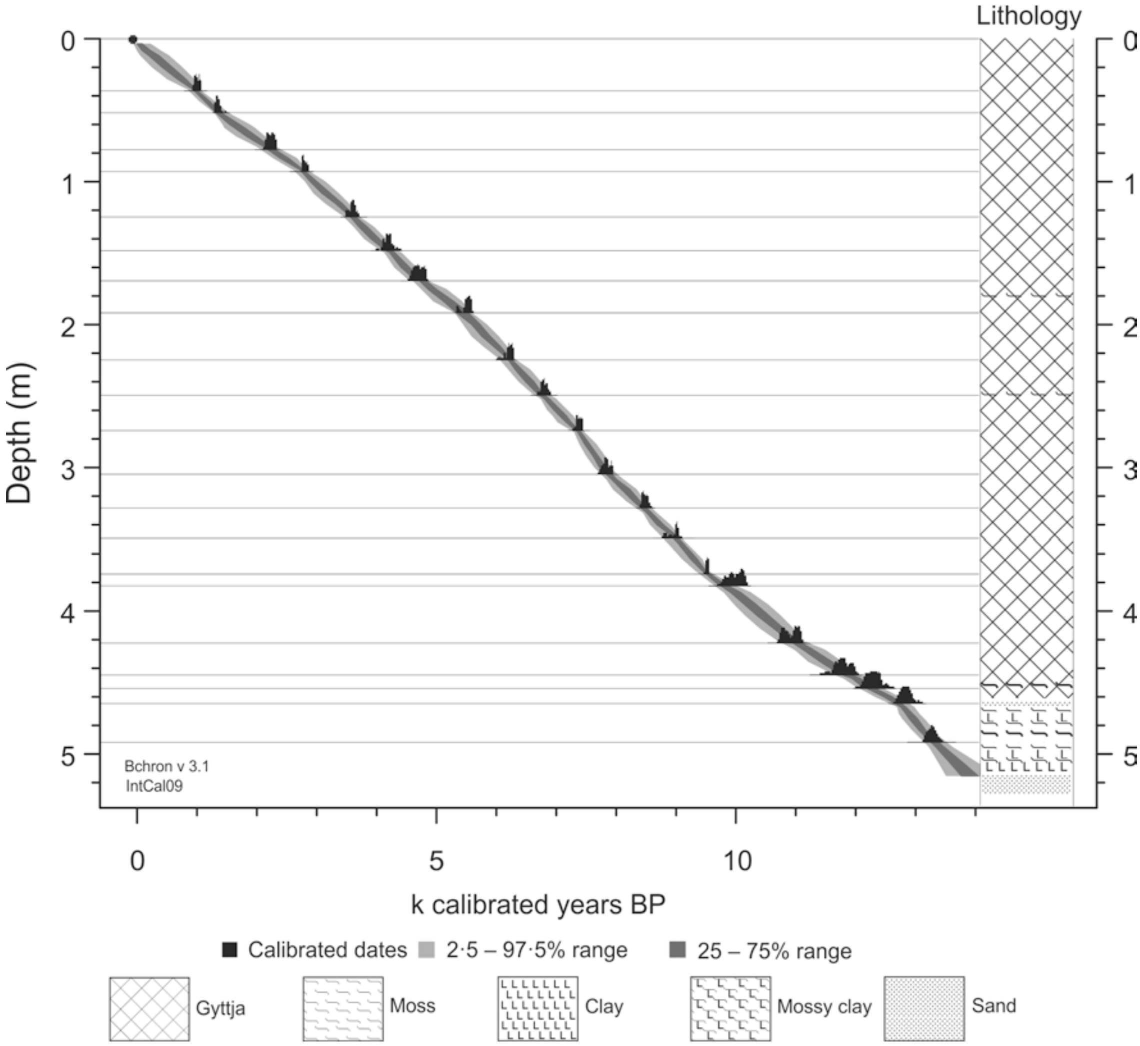

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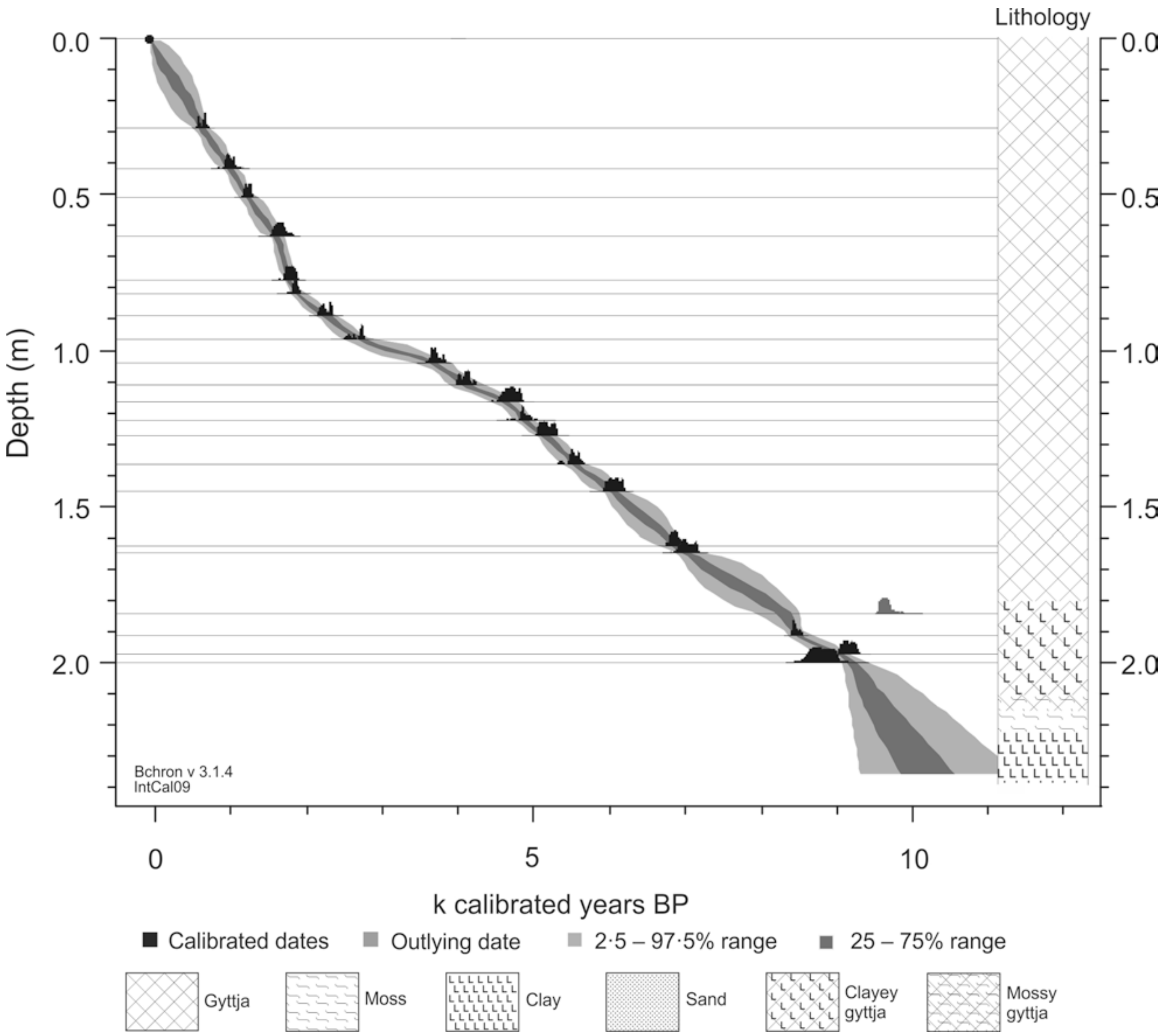

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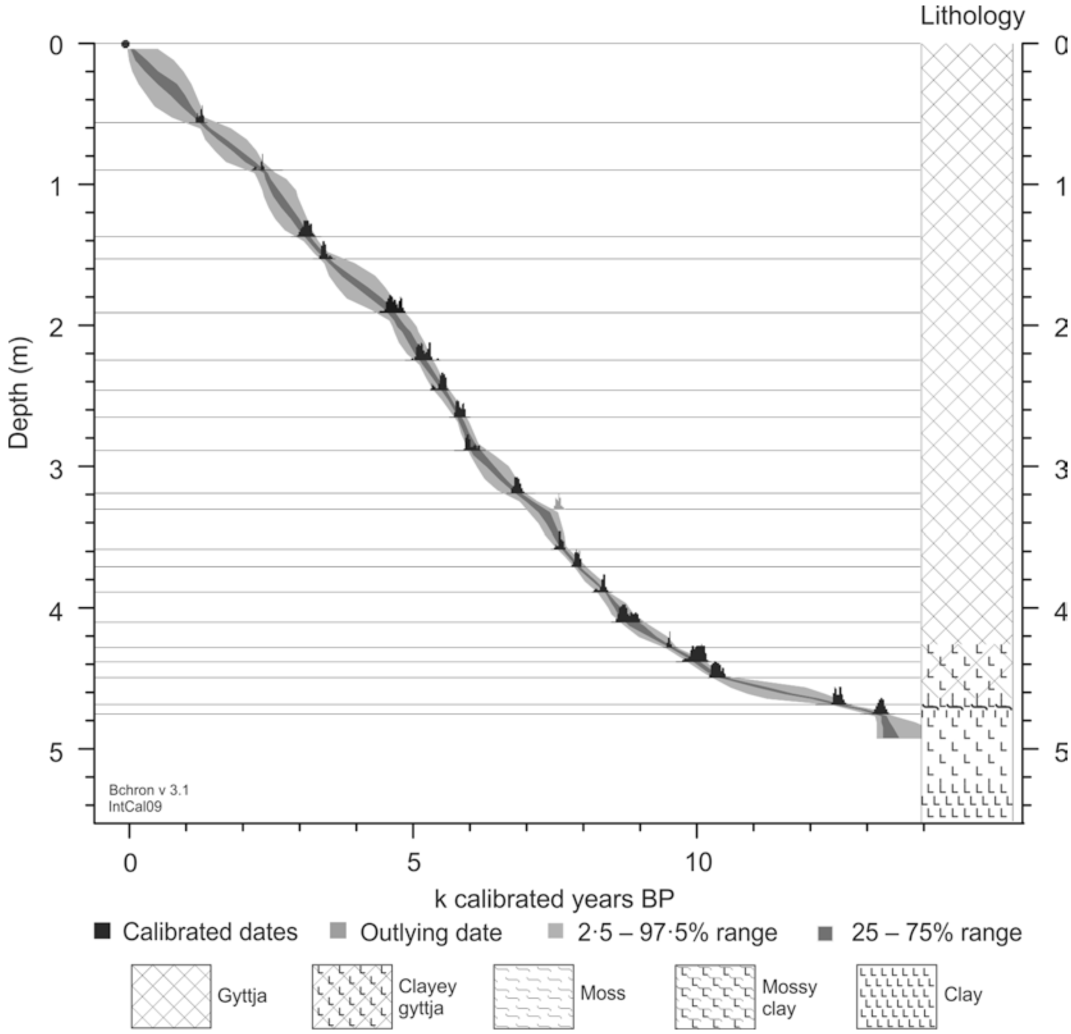

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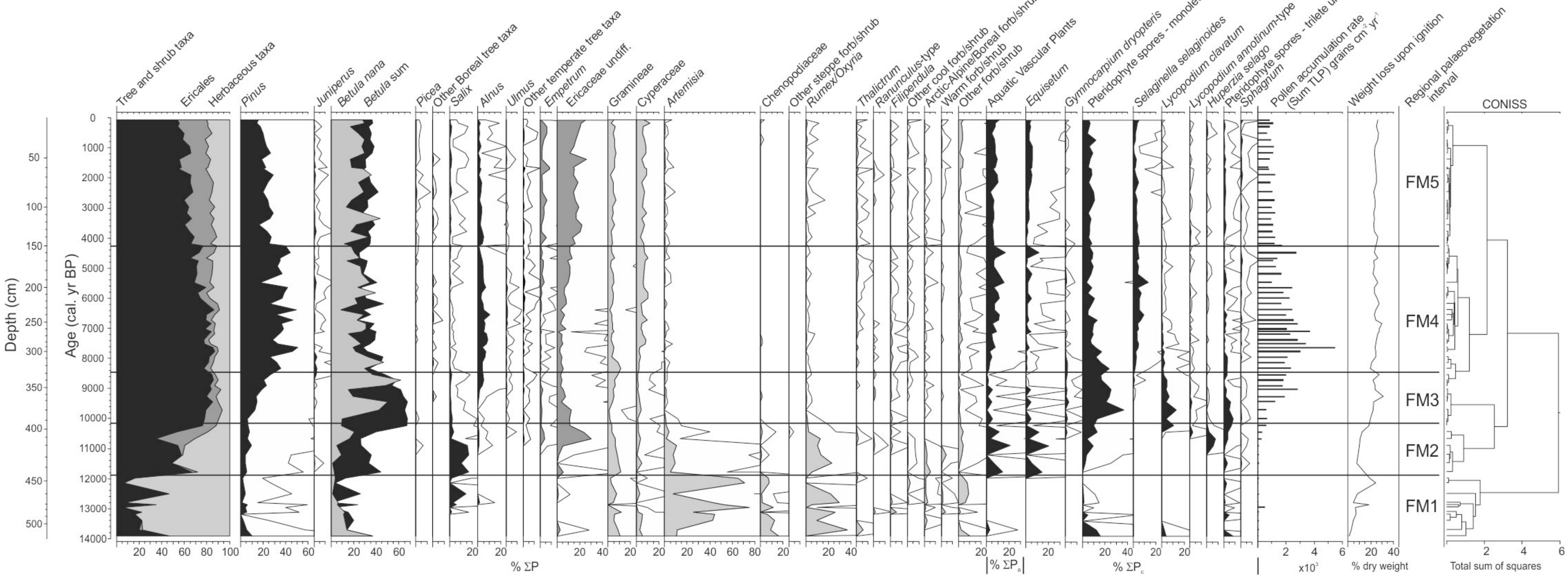

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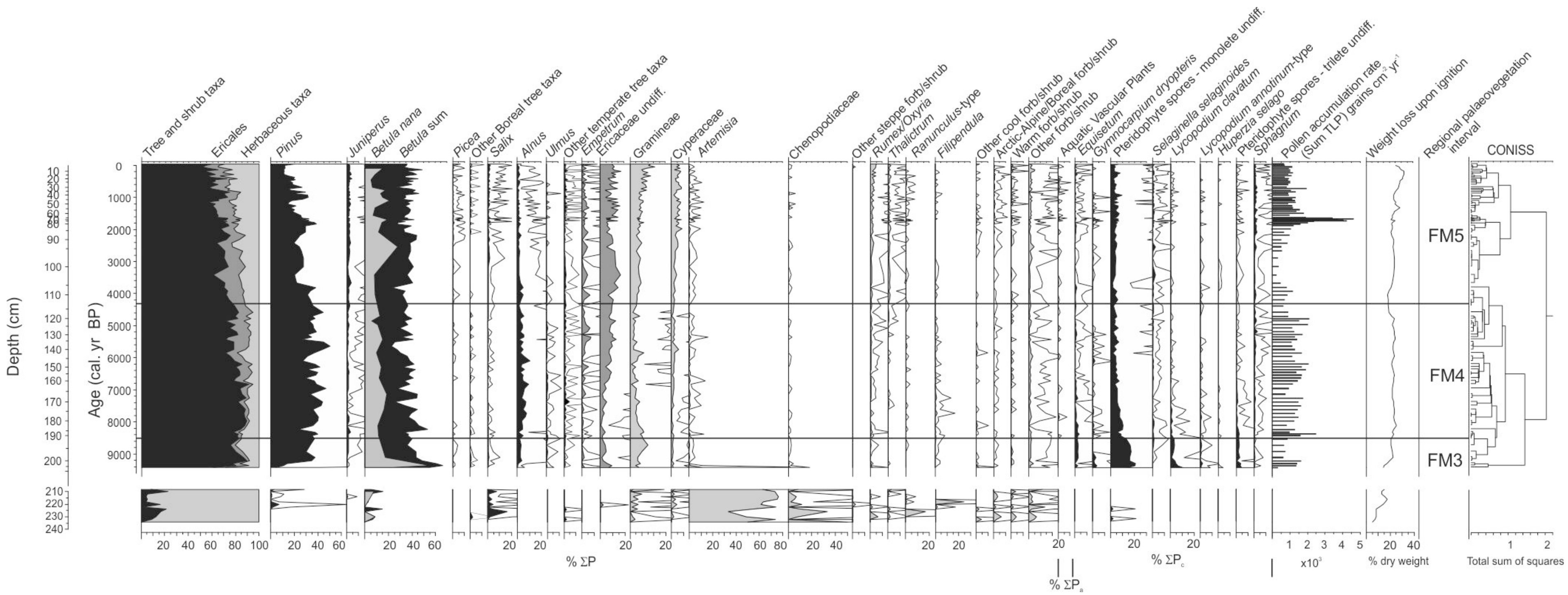

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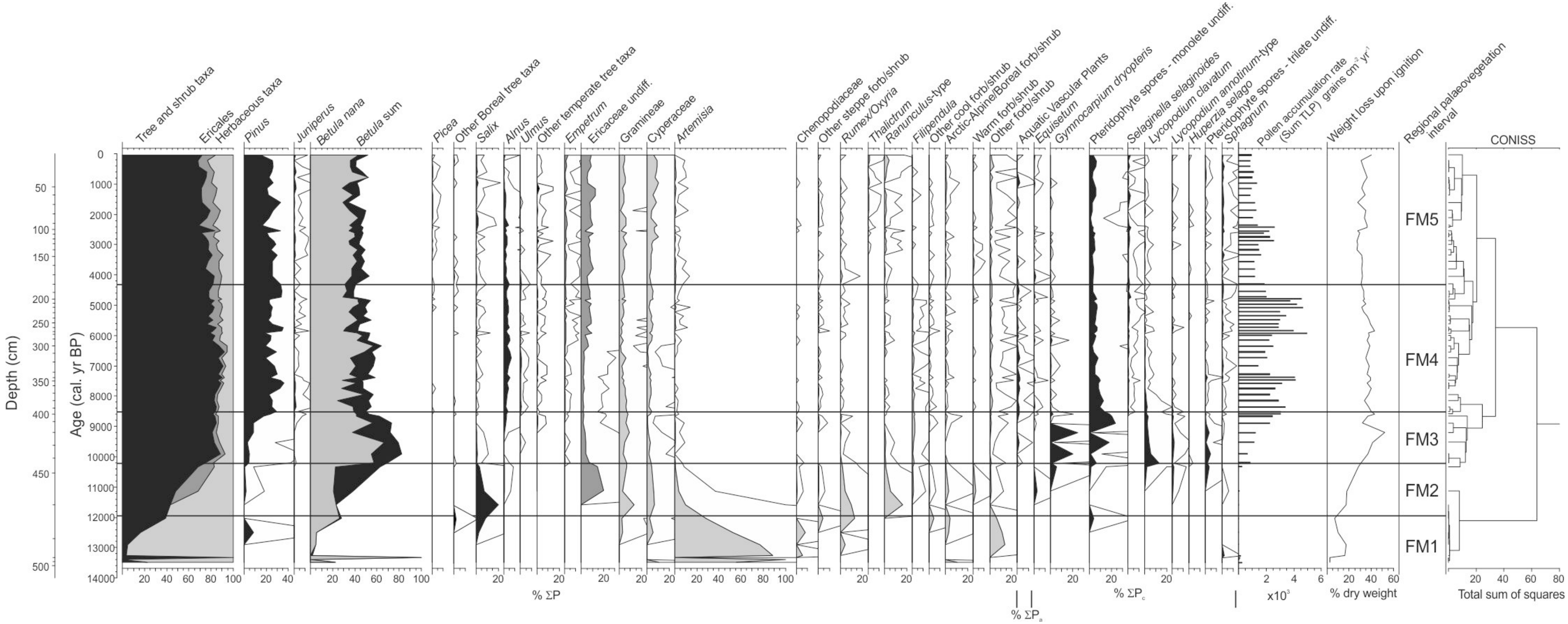
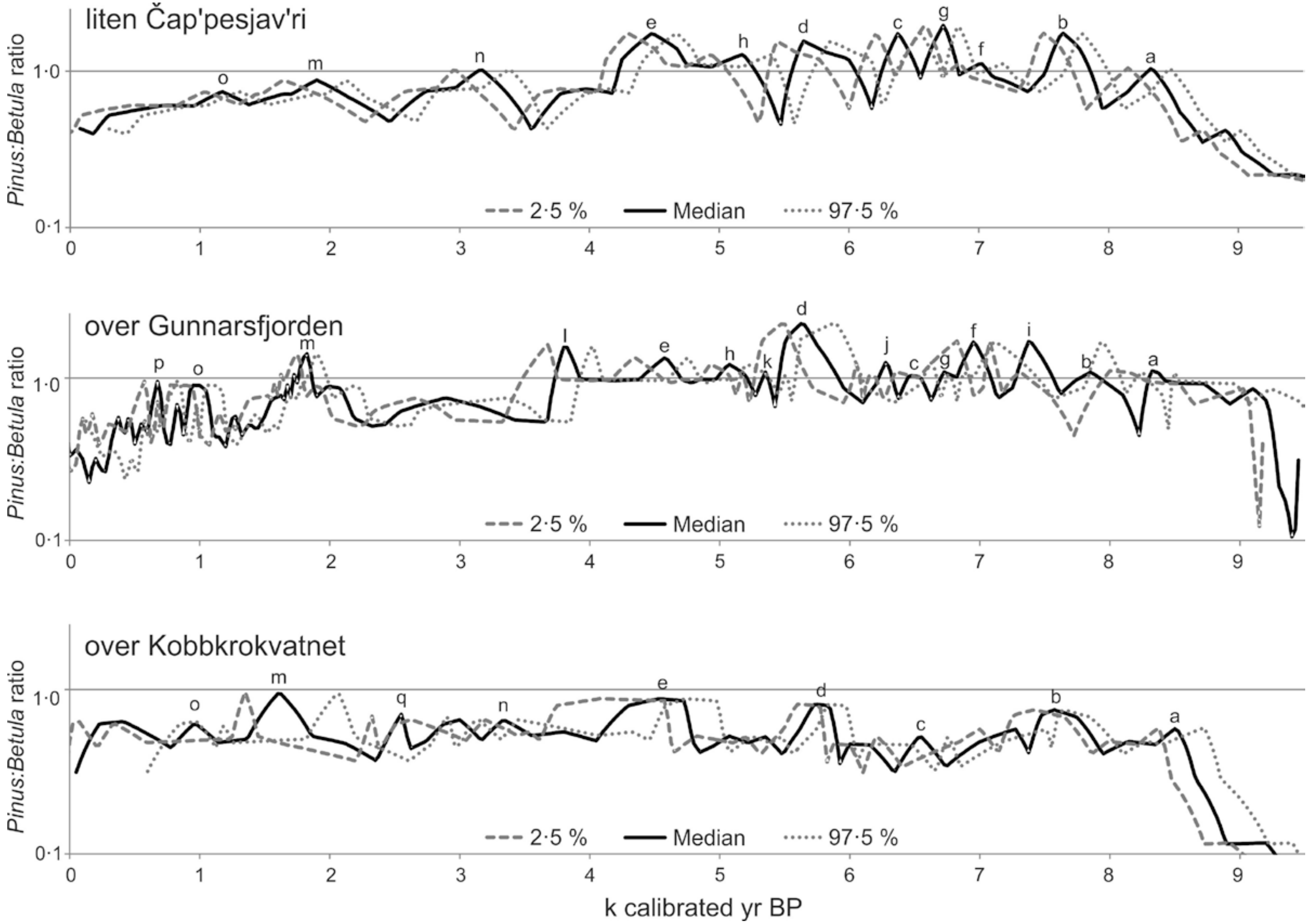


Figure 8: Pollen percentage diagram for over Kobbkrokvatnet



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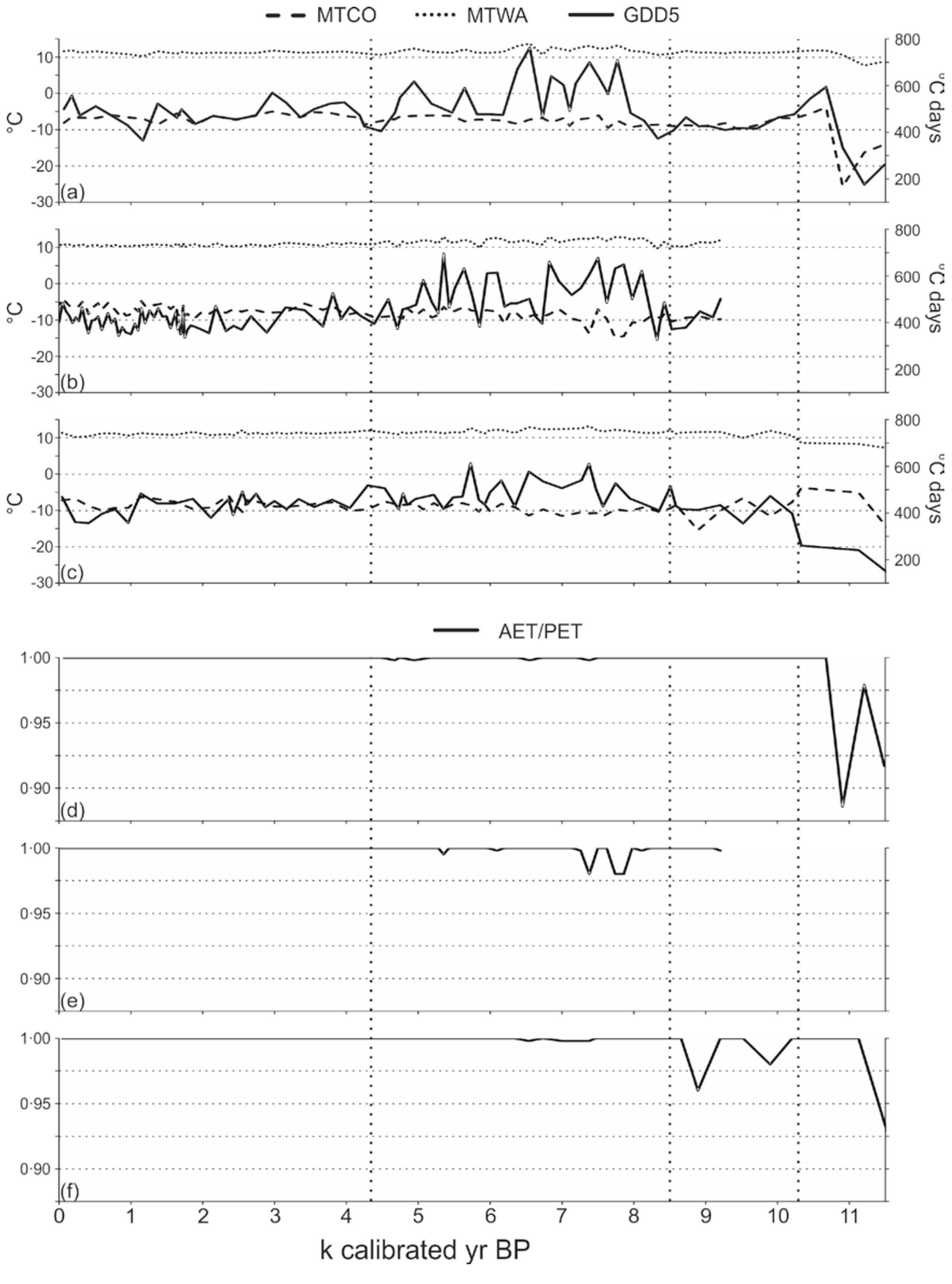

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