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Climate variability and long-term expansion of peat lands in Arctic Norway during the late Pliocene (ODP Site 642, Norwegian Sea)

S. Panitz¹, U. Salzmann¹, B. Risebrobakken², S. De Schepper², and M. J. Pound¹

¹Department of Geography, Faculty of Engineering and Environment, Northumbria University, Newcastle upon Tyne NE1 8ST, UK

²Uni Research Climate, Bjerknes Centre for Climate Research, Allégaten 55, 5007 Bergen, Norway

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Correspondence to: S. Panitz (sina.panitz@northumbria.ac.uk)

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Abstract

Little is known about the terrestrial response of high latitude Scandinavian vegetation to the warmer-than-present climate of the Late Pliocene (Piacenzian, 3.60–2.58 Ma). In order to assess Piacenzian terrestrial climate variability we present the first high resolution reconstruction of vegetation and climate change in northern Norway between 3.6–3.14 Ma. The reconstructions are derived from pollen assemblages in the marine sediments of ODP Hole 642B, Norwegian Sea (67° N). The palynological assemblages provide a unique record of latitudinal and altitudinal shifting of the forest boundaries, with vegetation alternating between cool temperate forest during warmer-than-present intervals, and boreal forest similar to today during cooler intervals. The northern boundary of the nemoral to boreonemoral forest zone was displaced at least 4–8° further north and warmest month temperatures were 6–14.5°C higher than present during warm phases. Warm climatic conditions persisted during the earliest Piacenzian (ca. 3.6–3.47 Ma) with diverse cool temperate nemoral to boreonemoral forests growing in the lowlands of the Scandinavian mountains. A distinct cooling event at ca. 3.47 Ma resulted in a southward shift of vegetation boundaries, leading to the predominance of boreal forest and the development of open, low alpine environments. The cooling culminated around 3.3 Ma, coinciding with Marine Oxygen Isotope Stage (MIS) M2. Warmer climate conditions returned after ca. 3.29 Ma with higher climate variability indicated by the repeated expansion of forests and peat lands during warmer and cooler periods, respectively. Climate progressively cooled after 3.18 Ma, resembling climatic conditions during MIS M2. A high variability of Norwegian vegetation and climate changes during the Piacenzian is superimposed on a long-term cooling trend. This cooling was accompanied by an expansion of *Sphagnum* peat lands that potentially contributed to the decline in atmospheric CO₂-concentrations at the end of the Piacenzian warm period and facilitated ice growth through positive vegetation-snow albedo feedbacks. Correlations with other Northern Hemisphere vegetation records suggest hemisphere-wide effects of climate cooling.

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1 Introduction

Preceding the glacial–interglacial cycles of the Pleistocene, the Late Pliocene (Piacenzian Stage, 3.60–2.58 Ma, Gibbard et al., 2010) marks the last time interval in Earth's history which was characterised by a sustained warmer-than-present climate (Lisiecki and Raymo, 2005). The mid-Piacenzian warm period (mPWP, 3.264–3.025 Ma) has recently been subject of intensive palaeoclimate research due to its similarity to projections of future global warming and its near-modern palaeogeography, palaeoceanography and palaeobiology (Dowsett, 2007; Dowsett et al., 2010; Haywood et al., 2013a; IPCC, 2013; Salzmann et al., 2009). During the mPWP average global mean annual surface temperatures were about 2–3 °C higher than present (Haywood et al., 2013b). As the mPWP exceeds orbital timescales its warmth was not driven by insolation changes but rather by differences in the state of boundary conditions intrinsic to the climate system itself (Haywood et al., 2013a; Miller et al., 2010; Pound et al., 2014). Relatively high atmospheric CO₂ concentrations with values of about 270–400 ppm have been identified as the most important cause of Piacenzian warmth while orography, vegetation and ice sheets constitute the remaining proportion of warming (Badger et al., 2013; Lunt et al., 2012; Martínez-Botí et al., 2015; Pagani et al., 2010; Seki et al., 2010).

In the North Atlantic and Nordic Seas both marine and terrestrial records reveal an increase in the magnitude of warming with increasing latitude during the Piacenzian. Sea surface temperatures (SSTs) were up to 8 °C warmer than present in the Nordic Seas as opposed to only ~ 2–4 °C in the mid-latitudes (Dowsett et al., 2013). The amplified warming has been suggested to be a cause of an enhanced Atlantic Meridional Overturning Circulation (AMOC) (Dowsett et al., 2013; e.g. Robinson, 2009). However, model simulations indicate a similar-to-present AMOC during the mPWP, supporting the notion that the amplified warming in the Nordic Seas was a result of increased radiative forcing (Zhang et al., 2013). On land, boreal taiga forests reached the coast of the Arctic Ocean during the Piacenzian, and tundra biomes were markedly reduced

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(Bennike et al., 2002; Rybczynski et al., 2013; Salzmann et al., 2008; Willard, 1996). In the high Arctic, Pliocene deposits reveal mean annual temperatures (MATs) $\sim 19^{\circ}\text{C}$ warmer than present, favouring the growth of larch-dominated forests on Ellesmere Island (Ballantyne et al., 2006, 2010; Rybczynski et al., 2013). In contrast, vegetation changes were less profound in the mid-latitudes. The prevalence of mixed forests in eastern Canada during the Piacenzian suggests a northward shift of the northern boundary of the deciduous forest zone by a minimum of 5° latitude with MATs $3\text{--}5^{\circ}\text{C}$ warmer than present (de Vernal and Mudie, 1989; Willard, 1994). In Norway, warm-temperate taxa occur at least 7° further north of their present limit, pointing towards substantially warmer conditions (Willard, 1994). A northward latitudinal shift of vegetation of about 10° is inferred from the presence of mixed to boreal forest on Svalbard during the Pliocene (Willard, 1996).

The mPWP has often been described as a relatively stable warm period with only minor temporal variations in climate and vegetation distribution (e.g. Willard, 1994; Thompson and Fleming, 1996). Up to the present, high resolution vegetation records with a robust age control are missing for the surroundings of the North Atlantic and Nordic Seas, and it is unclear whether the available palaeoclimate records represent the full variability or peak warm phases of the Piacenzian only. A recently published high resolution pollen record from Lake El'gygytyn in the north-eastern Russian Arctic reveals major changes in the dominant biome distribution during the Piacenzian, ranging from temperate cool mixed forests to Arctic shrub tundra vegetation (Andreev et al., 2014).

Data-model comparison studies for the mPWP suggest that climate models currently underestimate the magnitude of warming that is evident in proxy-based SST reconstructions for the Nordic Seas (Dowsett et al., 2013). The data-model discrepancy has been partly ascribed to the comparison of simulations that represent a discrete time interval to time-averaged proxy data (Dowsett et al., 2013; Salzmann et al., 2013). A recent model study indicates that the Norwegian Current, which strongly affects the climate of Norway, may have been cooler than present when altered palaeogeographic

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boundary conditions are considered (Hill, 2015). In order to resolve these uncertainties a time slice centred around 3.205 Ma (Marine Isotope Stage (MIS) KM5c) has been proposed for future palaeoclimate research in the Piacenzian, requiring high resolution proxy records (Haywood et al., 2013a).

Here we present a new high-resolution reconstruction of Piacenzian vegetation and climate changes for Arctic Norway based on the recently re-dated Ocean Drilling Program (ODP) sediment core 642B (Risebrobakken et al., 2015). The aim of this study is (1) to assess the evolution and temporal variability of vegetation and climate changes in Norway during the Piacenzian, (2) to determine their magnitude, and (3) to evaluate the potential of glacier and ice sheet built up on Scandinavia during cold intervals of the Piacenzian.

2 Geographical setting

2.1 Oceanographic location of ODP Hole 642B

ODP Hole 642B is located on the Outer Vøring Plateau in the Norwegian Sea about 400–450 km west of Norway (67°13.2' N, 2°55.8' E, 1286 m water depth, Shipboard Scientific Party (1987), Fig. 1). On either side of the Vøring Plateau a branch of the Norwegian Atlantic Current (NwAC) flows northward. The Eastern branch follows the continental slope of Norway and the Western branch flows around the Vøring Plateau. Atlantic Water is spread between those currents and lies above the site (Nilsen and Nilsen, 2007). The branches of the NwAC are an extension of the North Atlantic Current (NAC) which in turn is a continuation of the Gulf Stream (Orvik, 2002). The Eastern branch of the NwAC enters the Nordic Seas (Greenland Sea, Iceland Sea and Norwegian Sea) across the Iceland-Faroe Ridge while the Western branch flows through the Faroe-Shetland Channel (Hansen and Østerhus, 2000).

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2.2 Present-day climate and vegetation of Norway

As a result of the influence of the NAC and warm westerly and south-westerly winds, the climate of Norway is maritime with mild winters and higher MATs than any other area at comparable latitudes (Diekmann, 1994). Due to its geographic location and the Scandinavian mountains that run from north to south, the climate and vegetation of Norway changes along three gradients: latitudinal, altitudinal and continental (Moen, 1987). While MATs decrease with increasing latitude as well as altitude and continentality, precipitation decreases from west to east, being highest along the southwest coast of Norway (Diekmann, 1994).

The closest meteorological stations to ODP Hole 642B are located in Bodø (67° N) and Mo i Rana (66° N) (Fig. 1), for which climate data is available for the last 30 years from the Meteorological Institute of Norway. Present-day Mean Annual Temperatures (MATs) average -0.5°C with values ranging between ~ -2.5 and 1.7°C . Mean Cold Month Temperatures (CMTs, January) are -8.9°C but vary between ~ -13.3 and -3.5°C and Warm Month Temperatures (WMTs, July) reach 9.8°C on average, ranging between 5.8 and 13.8°C (Norwegian Meteorological Institute and Norwegian Broadcasting Corporation, 2014). In Norway precipitation follows a strong east–west gradient. In the southwest and some coastal areas further north Mean Annual Precipitation (MAP) amounts to more than $2500\text{mm}\text{year}^{-1}$. MAP ranges between 1000 and 2500mm along a broad south–north stretching coastal belt and only drops below 1000mm further inland. In the area around Bodø and Mo i Rana MAP is 1000 – 1500mm (Diekmann, 1994; Moen, 1999).

Most of Norway is covered by boreal and alpine vegetation today (Fig. 2). In the south, the boreal zone transitions into the temperate deciduous forests of Central Europe. In the north ($\sim 70^{\circ}\text{N}$) and at higher elevations, the boreal zone is limited by the tree line formed by birch (*Betula pubescens*) and borders the Arctic and alpine tundra (Moen, 1987, 1999). The altitudinal limit of the tree line above which alpine tundra dominates decreases gradually from $\sim 1200\text{m.a.s.l.}$ in the southern Scandina-

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vian mountains to sea level in northernmost Norway (Moen, 1999). The flora becomes less diverse and forest productivity as well as tree density decline from south to north (Moen, 1987). Temperate deciduous forest is only found along the far south coast and is characterised by the absence of *Picea abies* (Fig. 2) (Diekmann, 1994; Moen, 1987).

5 The boreal zone is divided into four subzones (boreonemoral, southern, middle and northern boreal zone, Fig. 2) that follow climatic gradients. The climate of the boreal zone is characterised by cold winters, long-lasting snow cover and a short growing season (Moen, 1987). The southernmost boreal zone (boreonemoral) mainly consists of *Pinus sylvestris* and *Picea abies*, with deciduous trees (e.g. *Acer platanoides*, *Fraxinus excelsior*, *Quercus* spp., *Tilia cordata* and *Ulmus glabra*) abundant under favourable local climatic conditions, especially on south-facing slopes (Diekmann, 1994). Presently, the boreonemoral zone extends over a continuous area in southern Norway, but also occurs sporadically up to $\sim 64^\circ$ N (Moen, 1987). The northern boreonemoral limit is defined by the northernmost distribution of *Quercus* forest, but the absence of oak forest in central Norway might also be due to geographical barriers (Diekmann, 1994; Moen, 1987).

15 In the southern boreal zone deciduous forest are still present and wide areas are covered by raised bogs. The latitudinal boundary between the southern and middle boreal zone, dominated by coniferous forests, is located at $\sim 67^\circ$ N (Fig. 2). Raised bogs reach their upper limit in this zone (Moen, 1987). Along the coast the middle boreal zone extends to about 70° N where it transitions into the northern boreal zone, consisting of sparsely growing coniferous forest, a broad belt of birch forest (especially at higher altitudes in southern to central Norway), and peat lands (Moen, 1987). Beyond the northern boreal zone at higher latitudes and altitudes extend alpine regions with grass-heaths communities (Moen, 1987).

25 Moen (1987) and Diekmann (1994) both separate a coastal section along the west and southwest coast of Norway that is distinct in climate and vegetation. Climatically, the coastal area is associated with mild winters, relative cool summers and frequent precipitation. The modern vegetation, however, has been significantly altered by human

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activity, with the present dominance of open heathland (*Calluna vulgaris*) ascribable to logging and continuous burning and grazing cycles (Moen, 1987). Atlantic raised bogs that naturally lag any marginal forest stretch along the coast and the remaining forest stands are composed of *Alnus* spp., *Betula* spp., *Corylus avellana*, *Fraxinus excelsior*, *Pinus sylvestris* and *Quercus* spp. (Diekmann, 1994; Moen, 1987).

2.3 Orography

At present mountains reach a maximum elevation of 1500 m in the areas surrounding Bodø and Mo i Rana with the tree line being lowest near the coast (400–500 m a.s.l.) and reaching elevations of up to 800 m a.s.l. further inland (Moen, 1999). During the Piacenzian the Scandinavian mountains had already been uplifted, they were, however, lower than present (Anell et al., 2009; Knies et al., 2014). Anell et al. (2009) report uplift of ~ 1 km in northern Norway and 1–1.5 km in the southern Scandinavian mountains during the Neogene. These estimates correspond to the height of the Scandinavian mountains of 500 to 1000 m that was used for the PRISM3 reconstruction of Pliocene climate (Sohl et al., 2009), reducing them by 500–1000 m in altitude compared to present.

3 Materials and Methods

3.1 Sample preparation and pollen analysis

A total of 70 samples were taken from ODP Hole 642B of which 68 samples are situated between 69.90 and 66.95 meter below sea floor (m.b.s.f.) (Shipboard Scientific Party, 1987). Additionally two surface samples were taken at 0 and 3 cm below sea floor from the same core in order to compare the Piacenzian to modern pollen assemblages. All samples were pre-sieved in Bergen, Norway to retain foraminifera for oxygen isotope analysis (Risebrobakken et al., 2015). After sieving, the < 0.063 mm fraction of the samples was prepared for palynological analysis at the Palynological Laboratory

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3.2 Age model

The Pliocene age model for ODP Hole 642B is based on the magnetic stratigraphy of Bleil (1989) updated to the Astronomically Tuned Neogene Time Scale (ATNTS) 2012 (Hilgen et al., 2012), and further correlation of the benthic oxygen isotopes to the global LR04 benthic $\delta^{18}\text{O}$ stack (Lisiecki and Raymo, 2005; Risebrobakken et al., 2015). Across glacial MIS M2, the benthic $\delta^{18}\text{O}$ signal is not any heavier than during other times of the Pliocene. This points, in conjunction with a lack of increased ice rafted debris input, to the possibility of a hiatus for the globally coldest part of MIS M2. A major hiatus exists after 3.14 Ma (Jansen and Sjøholm, 1991; Risebrobakken et al., 2015).

The investigated samples have an age range of 3.60 to 3.14 Ma. The upper part of the sequence, which coincides with the PRISM interval, has been counted in high resolution (800 to 14 700 years) and covers the central part of interglacial MIS KM5c (3.205 Ma). The earlier part of the Piacenzian was analysed in lower resolution (6600 to 23 300 years) in order to analyse the main climatic states and trends.

The modern surface sample presumably covers less than 2000 years while the sub-surface sample at 3 cm depth possibly reveals a maximum age of 6000 years. These assumptions are based on a modern sedimentation rate of $< 2 \text{ cm kyr}^{-1}$ (Romero-Wetzel, 1989).

3.3 Climate reconstruction

To obtain quantitative estimates of Piacenzian climate the Coexistence Approach (CA) of Mosbrugger and Utescher (1997) was applied. This approach uses the modern climatic tolerances of the Nearest Living Relatives (NLRs) of the fossil taxa present in an assemblage to determine the climatic range in which these taxa could coexist. Climatic ranges have been quantified for Mean Annual Temperature (MAT), Coldest Month Temperature (CMT), Warmest Month Temperature (WMT), and Mean Annual Precipitation (MAP) (Utescher and Mosbrugger, 2013).

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Several requirements with regard to the inclusion of samples and taxa were defined before applying the CA to ensure accurate and reliable palaeoclimate estimates. Only samples with a minimum of eight NLR taxa were used to determine the palaeoclimatic range in order to obtain narrower intervals. This led to the exclusion of two samples with a total count of less than 100 pollen grains. Rare taxa, comprising less than 1 % of the assemblages, were excluded from the analysis to account for misidentification and the uncertainty caused by long distance transport of pollen grains.

4 Results

4.1 Modern pollen assemblages

The two analysed modern surface and subsurface samples show pollen concentrations of 238 and 294 grains g^{-1} sediment, respectively (Fig. 3). Percentages of *Pinus* pollen (45–52 %) and *Sphagnum* spores (14–32 %) are highest in the two samples. Pollen of other conifers (*Picea*, *Juniperus*-type, *Taxus*) are represented by proportions of less than 4 %, but Cupressaceae pollen accounts for $\sim 10\%$ of the assemblage in the subsurface sample. The relative abundance of *Lycopodium* spores and undifferentiated monolet spores is also relatively high, with $\sim 6\text{--}15\%$ and $\sim 9\%$, respectively. *Betula* is the most common deciduous tree pollen. *Alnus*, *Corylus*, Ericaceae, *Fraxinus*, *Ilex aquifolium* and *Myrica* pollen occur in very low numbers. Compared to the subsurface sample, the surface sample reveals a higher diversity of herb pollen (Asteraceae, Brassicaceae, Cyperaceae, and Fabaceae). The proportion of reworked pollen and spores is relatively high in both samples (21–32 %).

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4.2 Piacenzian pollen assemblages

4.2.1 Pollen Zone 1 (69.9–69.0 m b.s.f., ca. 3.60–3.47 Ma, 13 samples)

Pollen Zone (PZ) 1 is characterised by a high abundance of *Pinus* pollen (60.7–77.2 %) and pollen from other conifer trees (*Picea*, Cupressaceae, *Juniperus*-type, *Sciadopitys* and *Tsuga*) (Figs. 4 and 6). *Juniperus*-type, *Sciadopitys* and *Tsuga* pollen reveal their maximum abundances of the entire pollen record with up to ~ 22, 18 and 10 %, respectively, within this zone. Ericaceae pollen reaches a maximum of 16.5 % in the middle of the zone and subsequently decreases to values of around 6 % towards the upper part. *Alnus*, *Betula*, *Corylus*, *Quercus* and *Ulmus* pollen is frequently present whereas other deciduous tree pollen such as *Carpinus* and *Carya* occurs only sporadically (Fig. 4). The abundance of herb pollen is generally low throughout PZ 1. The number of *Lycopodium* (including *L. annotinum*, *L. clavatum*, *L. inundatum* and *L. spp.*) spores is relatively high in the early part (up to ~ 34 %), declining continuously throughout the interval. The relative abundance of *Sphagnum* spores is relatively constant, showing its lowest values (< 22 %) within the entire study interval (Fig. 6). Spores of *Huperzia*, *Osmunda*, Polypodiaceae and undifferentiated monoletes are regularly found (Fig. 4). Rare pollen taxa only occur sporadically and the average diversity index across the zone is relatively low (Figs. 5 and 6). Pollen concentrations mostly vary between ~ 1000–1500 grains g⁻¹ sediment and peak at a maximum of 3900 grains g⁻¹ sediment in the upper part of the zone. Reworked pollen and spores occur in low numbers with a maximum percentage of 4.4 % (Fig. 4).

4.2.2 Pollen Zone 2A (69–68.54 m b.s.f., ca. 3.47–3.35 Ma, 9 samples)

The amount of *Pinus* remains high (65.1–75.2 %) throughout PZ 2A while percentages of *Picea* pollen decreases (Fig. 4). Pollen of other conifer trees (Cupressaceae, *Juniperus*-type, *Sciadopitys* and *Tsuga*) shows a sharp decrease in numbers at the lower pollen zone boundary (Figs. 4 and 6). Ericaceae pollen increases to maximum

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values of $\sim 18\%$ in the upper part of the zone. The proportion of deciduous tree pollen is generally low. *Betula* pollen is consistently present while the proportion of *Alnus* and *Corylus* pollen peaks in the middle of PZ 2A. Pollen of Asteraceae, especially Asteraceae Liguliflorae-type, shows maximum values of up to 31% in this zone while other herb pollen remains low in abundance (Figs. 4 and 6). *Lycopodium* spores peak in the lower and upper parts of PZ 2A, reaching proportions of up to 56%. A peak in the abundance of *Sphagnum* spores (43%) is observed in the lower part of the zone (Fig. 6). *Osmunda* spores show highest abundance and subsequently decrease until it disappears from the assemblage in the upper part. *Huperzia* spores become more abundant and undifferentiated monolete spores are continuously present. *Pteridium* spores are also regularly found (Fig. 4). The number of rare pollen taxa is very low and the diversity index shows a similar average value to PZ 1 (Figs. 5 and 6). Pollen concentrations reach maximum values of ~ 1900 grains g^{-1} sediment within the zone. Reworked pollen and spores first reach a relatively high proportion (8.6%) in the middle part of this zone and peak again, after declining to values of $< 3\%$, in the upper part of the zone ($\sim 15\%$) (Fig. 4).

4.2.3 Pollen Zone 2B-1a (68.54–68.365 m b.s.f., ca. 3.35–3.29 Ma, 5 samples)

The proportion of *Pinus* pollen is slightly reduced when compared to PZ 1 and 2A with percentages ranging between 43–66% (Fig. 4). Other conifer pollen remains low in abundance. Ericaceae pollen shows percentages of less than 10%. *Alnus*, *Betula* and *Corylus* pollen is continuously present whereas more temperate pollen taxa like *Carpinus* and *Carya* is absent. Asteraceae Liguliflorae-type pollen shows a pronounced peak (ca. 10%) in the lower part of the zone while other herb pollen taxa only occur sporadically and in low numbers (Fig. 4). *Lycopodium* spores reach their highest abundance in the lower part of the zone. A subsequent decline in the relative abundance of *Lycopodium* spores is accompanied by a distinct increase in *Sphagnum* spores, reaching proportions of up to $\sim 63\%$ in the upper part of the zone (Fig. 6). The number of rare pollen taxa remains very low. The average diversity index is slightly higher when com-

pared to PZ 1 and 2A (Fig. 6). Pollen concentrations are relatively low with maximum values of ~ 500 grains g^{-1} sediment (Fig. 4).

4.2.4 Pollen Zone 2B-Ib (68.365–67.09, ca. 3.29–3.16, 36 samples)

PZ 2B-Ib exhibits the highest sample density and shows a high variability which is superimposed by a prevailing change in abundances (Figs. 4 and 6). *Pinus* pollen shows relatively high values (43–79 %) in the lower part of the zone alongside an increased proportion of pollen from other conifer trees (Cupressaceae, *Juniperus*-type, *Picea*, *Sciadopitys* and *Tsuga*). Subsequently the proportion of *Pinus* pollen stays around 50 % before steadily increasing to a maximum of ~ 65 % in the upper part of the zone.

Peaks in *Pinus* pollen are concurrent with higher abundances of the other conifer pollen (Figs. 4 and 6). The relative abundance of Ericaceae pollen does not exceed 15 %. *Alnus*, *Betula*, *Corylus* and *Quercus* pollen occurs frequently in low percentages (< 9 %). Other deciduous tree pollen, such as *Carpinus*, *Carya*, *Ostrya*, *Pterocarya*, *Ulmus*, as well as pollen of the evergreen shrub *Ilex aquifolium* is found regularly within PZ 2B-Ib in low percentages. Asteraceae Liguliflorae-type pollen never exceeds 6 % throughout the zone. Although still low in abundance comparatively more taxa of herb pollen is present in this interval. Pollen of *Artemisia* as well as the families Apiaceae and Cyperaceae first appears in this pollen zone (Fig. 4). *Lycopodium* spores show a general decrease in abundance throughout the interval and alternate with high proportions of *Sphagnum* spores. After reaching a minimum of 11 % the proportion of *Sphagnum* spores increases, reaching ~ 68 % in the upper part (Fig. 6). Spores of *Huperzia*, *Osmunda*, Polypodiaceae, *Pteridium* and undifferentiated monolete spores occur frequently (Fig. 4). The number of rare pollen taxa is highest in this pollen zone (Fig. 5). In the lower part of the zone the diversity index shows a high variability with the same average value as PZ 2B-Ia. Subsequently, the average diversity index of PZ 2B-Ib increases markedly (Fig. 6). Pollen concentrations peak in the lower part (max. 2100 grains g^{-1} sediment) and again in the middle part of the zone (max. 4300 grains g^{-1} sediment) (Fig. 4). These high values can be ascribed to an increased sedimentation rate (Rise-

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brobakken et al., 2015). The proportion of reworked pollen and spores is highest between 68.05 and 67.55 m.b.s.f., reaching values of up to 12.5% and stay below 7% outside the interval (Fig. 4).

4.2.5 Pollen Zone 2B-II (67.09–66.95 m b.s.f., ca. 3.16–3.14 Ma, 5 samples)

5 The amount of *Pinus* pollen varies between ~ 32 and 48% and thus shows its lowest percentages within the entire Piacenzian record (Fig. 4). Pollen concentrations are also relatively low (< 580 grains g⁻¹ sediment). While *Picea* and Ericaceae pollen decreases, *Juniperus*-type pollen percentages increase. Single pollen grains of *Sciadopitys* are still found whereas pollen of *Tsuga* is absent. *Alnus*, *Betula* and *Corylus* pollen is consistently present while pollen of other deciduous trees (*Carya*, *Ostrya*, *Pterocarya*, and *Quercus*) only occurs sporadically. The diversity of herb pollen is reduced compared to PZ 2B-Ib (Fig. 4). *Lycopodium* spores are relatively low in abundance (< 21%) whereas the proportion of *Sphagnum* spores is high (up to ~ 62%) (Fig. 6). *Huperzia* and undifferentiated monoletes spores peak in the upper part of the zone. Rare pollen taxa are present in relatively low numbers and the average diversity index remains unchanged when compared to PZ 2B-Ib (Figs. 5 and 6). Pollen concentrations are low with values < 600 grains g⁻¹ sediment. Reworked pollen reaches proportions of up to 12% (Fig. 4).

4.3 Quantitative palaeoclimate estimates

20 Piacenzian MATs based on the CA range between 3.7 and 15.8°C in the majority of samples, suggesting MATs 4.2–16.3°C higher than present (Fig. 7). CMTs show values between -8.4 and 3.7°C, encompassing higher-than-present temperature ranges of 0.5–12.6°C. The CA reconstructs WMTs of 15.8–24.3°C for most pollen assemblages, implying a rise of summer temperatures of 6–14.5°C when compared to modern values. MAP values are confined to 1300–1741 mm in the lower part and overlap with

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vegetation records (Bjune and Birks, 2008; e.g. Bjune, 2005) but are only represented in low numbers (< 3%) in the marine surface pollen assemblages, complicating the quantification of their representation in the vegetation. The same applies for *Corylus* which is a warmth-loving, oceanic climate species in Norway and reaches its upper limit in the middle boreal zone, thus growing up to 70° N (Bjune, 2005; Moen, 1987). Other warmth-loving taxa such as *Fraxinus*, *Ilex* and *Taxus* that are restricted to southern Norway (< 62.5° N) (Moen, 1987, 1999) are represented with a relative abundance of up to 2% in the modern pollen samples of Hole 642B, suggesting pollen input from a large source area. Human activity has, however, significantly altered the natural vegetation of Norway (Moen, 1987, 1999), resulting in the occurrence of species outside their natural habitat, which could explain the presence of *Fraxinus* and *Taxus* in the modern samples. The similar relative abundance of all deciduous tree pollen also hampers the unequivocal definition of a threshold for the inclusion/exclusion of taxa in palaeoclimate reconstructions. Hereafter, taxa that occur with a proportion of less than 1% in the fossil assemblages are excluded from any quantitative palaeoclimate estimates. Pollen taxa that are regularly abundant with percentages > 1% are considered to be representative of the vegetation at roughly the same latitude as the coring site.

5.2 Vegetation and climate at 3.60–3.47 Ma

At the onset of the Piacenzian the occurrence of pollen from deciduous temperate elements (e.g. *Carpinus*, *Carya* and *Quercus*) together with high abundances of pollen from conifer trees, including temperate taxa such as *Sciadopitys* and *Tsuga*, suggest the presence of cool temperate deciduous to mixed forest in northern Norway. At present, *Quercus* spp. are a distinctly southern species in Norway, occurring in the nemoral and boreonemoral zone (Fig. 2). During the earliest Piacenzian the northern boundary of the boreonemoral zone was presumably positioned at least 4° further north when compared to today, reaching the Arctic Circle. Predominantly deciduous forest might even have prevailed in the lowlands of northern Norway, implying a northward shift of the northern limit of the nemoral zone by at least 8° latitude.

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Sciadopitys and *Tsuga* are considered to be part of the cool temperate montane vegetation. Both species went extinct in Europe during the glacial–interglacial cycles of the Pleistocene but can still be found in East Asia and North America (Svenning, 2003; e.g. Wen, 1999). Only one species of *Sciadopitys* still exists at present, growing in the warm to cool temperate montane zone of Japan. There, *Sciadopitys* forests are associated with steep rocky ridges or slopes, requiring relatively dry habitat conditions in a humid climate (Ishikawa and Watanabe, 1986). In Neogene deposits from central Europe and Denmark *Sciadopitys* is, however, known to be an element of peat-forming vegetation or conifer forests that grew in better drained or elevated areas, respectively, suggesting that its ecological requirements have changed (Figueiral et al., 1999; e.g. Schneider, 1995). In the Lake Baikal region *Tsuga-Picea* forests are also ascribed to habitats at higher altitudes during the Piacenzian (Demske et al., 2002). Our assignment of *Sciadopitys* and *Tsuga* to montane conifer forests is supported by the correlation of the relative percentage changes of these taxa to those of other high-altitude taxa (Cupressaceae, *Juniperus-type*, *Picea*; Fig. 4) (e.g. Numata, 1974; Seppä and Birks, 2001).

Ericaceae shrubs, *Lycopodium* and *Sphagnum* mosses likely originated from both the understorey of the cool temperate to boreal forests and open environments. The relative abundance of *Sphagnum* spores during the earliest Piacenzian is lower than that in the surface sample but similar to the subsurface sample (Figs. 3 and 4) which might be indicative of a less extensive distribution of peat lands.

Warmer-than-present climatic conditions between 3.55 and 3.48 Ma have also been recorded at Lake El'gygytgyn in the north-eastern Russian Arctic where *Larix/Pseudotsuga* forests predominated (Andreev et al., 2014; Brigham-Grette et al., 2013). In southern East Siberia mixed coniferous forests grew under a relatively warm climate in the Lake Baikal region during the early Piacenzian (Demske et al., 2002).

5.3 Vegetation and climate at 3.47–3.35 Ma

A marked cooling around 3.47 Ma and a subsequent establishment of similar-to-present boreal conditions are inferred from a sharp drop in the relative abundance

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of conifer tree pollen (except *Pinus* pollen). A corresponding increase in the abundances of spores and pollen from herbs, shrubs and mosses (Asteraceae, Ericaceae, *Lycopodium* and *Sphagnum*; Fig. 4) indicates the development of open environments at high altitudes, possibly similar to the modern low alpine vegetation. At present the lower boundary of the low alpine zone, corresponding to the tree line, is reached at 400–800 m in the area around Bodø and Mo i Rana (Moen, 1999).

Maximum abundance of herb pollen, especially those of Asteraceae Liguliflorae-type are reached at 3.42 Ma, steadily declining towards 3.35 Ma (Figs. 4 and 6). They are indicative of drier conditions. At present tall-herb meadows reach their distribution limit in the southern Arctic zone in northern Norway but are less common in the alpine regions (Moen, 1999). The high abundance of Asteraceae in ODP Hole 642B might reflect a vegetation community with no modern analogue. At present alpine environments with abundant Asteraceae can only be found in the Southern Hemisphere. At Kosciuszko National Park, New South Wales, Australia, Asteraceae grows in alpine herbfields, grasslands, bogs and heath communities along with Ericaceae, *Huperzia*, *Lycopodium* and *Sphagnum* (Costin et al., 2000). Additionally, Asteraceae and Ericaceae pollen as well as *Lycopodium* and *Sphagnum* spores in the sediments of ODP Hole 642B might have also originated from the field layer of forests covering the lower altitudes. These were more boreal in character during this time interval with *Pinus* as the dominant species as indicated by low percentages of pollen from other conifers, including the temperate taxa *Sciadopitys* and *Tsuga* (Fig. 4). The diversity index shows the lowest average value across this time interval, aiding the interpretation of the prevalence of low diverse boreal forest and relative cool climatic conditions (Fig. 6).

The development of open environments at high altitudes implies an altitudinal downward shift of vegetation belts as well as a southward displacement of vegetation zones. Taxa characteristic of the boreonemoral zone (e.g. *Quercus*, *Sciadopitys*) comprise low proportions in the pollen assemblage at ODP Hole 642B between ca. 3.47 and 3.35 Ma (Fig. 4), suggesting that patches of deciduous to mixed forests grew in the area. These patches presumably represent extensions of the northern boundary of the mixed forest

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zone. The prevalence of boreal forest together with patchy deciduous forest stands and low alpine environments at higher altitudes is indicative of climatic conditions similar to today. Assuming tree line elevations of 400–800 m, the northern Norwegian mountains were probably not high enough for mountain glaciers to establish between 3.47 and 3.35 Ma. Presently, glaciers only form in the high alpine zone, above 1000 m (Moen, 1987, 1999).

While the Hole 642B pollen record indicates stable cold conditions similar to present-day (Figs. 4 and 6), re-occurring warmer and cooler climate conditions are documented in the Lake El'gygytyn and Lake Baikal region between 3.47 and 3.35 Ma (Table 1; Andreev et al., 2014; Demske et al., 2002). As in ODP Hole 642B, the pollen percentages of thermophilic tree species (*Abies*, *Picea* and *Tsuga*) also decrease significantly between ca. 3.48 and 3.45 Ma. At the same time, increased percentages of Poaceae and Cyperaceae pollen as well as *Sphagnum* and other spores indicate the development of open habitats, suggesting cooler and reoccurring drier and wetter climatic conditions around Lake El'gygytyn (Andreev et al., 2014). The peak in *Sphagnum* spores at ca. 3.43 Ma in ODP Site 642B coincides with an increase in *Sphagnum* spores in the Lake El'gygytyn record, suggesting wetter climatic conditions both in Norway and the Siberian Arctic. A biome reconstruction for Lake El'gygytyn suggests the first appearance of tundra during a cool interval, lasting from 3.39 to 3.31 Ma (Andreev et al., 2014). A thinning of the forests and spread of Ericaceae shrubs and Lycopodiaceae is also recorded at Lake Baikal at 3.47 Ma (Demske et al., 2002). Between 3.5 and 3.38 Ma drier but still relatively warm climatic conditions are inferred from a change of moist (*Abies*, *Picea* and *Tsuga*) to dry (*Juniperus*-type, *Quercus*, *Larix/Pseudotsuga*) forests (Demske et al., 2002). A strong cooling is observed in the Lake Baikal region at 3.39 Ma by a spread of boreal taxa and a maximum in *Selaginella selaginoides* (Demske et al., 2002).

The period of cooling in Scandinavia, north-eastern Russian Arctic and southern East Siberia corresponds to the time of deposition of till, and hence glaciation, in the James Bay Lowland, Canada (~ 52° N) at ca. 3.5 Ma (3.6–3.4 Ma) (Gao et al., 2012),

and also to enriched global benthic $\delta^{18}\text{O}$ (Lisiecki and Raymo, 2005). No major glacial events are, however, evident in the Nordic Seas during this time interval (Fronval and Jansen, 1996; Kleiven et al., 2002). Gao et al. (2012) propose that the lack of ice-rafted detritus in the Nordic Seas either indicates a significant contribution from the North American ice sheet to the elevated benthic $\delta^{18}\text{O}$ values or a restriction of glaciation to the continental interior of Greenland and Fennoscandinavia. The Piacenzian vegetation record for northern Norway suggests a wide distribution of boreal forest between 3.47 and 3.35 Ma with no evidence of mountainous glaciation if a lapse rate of $6.5^\circ\text{C km}^{-1}$ is assumed.

5.4 Vegetation and climate at 3.35–3.29 Ma

After ca. 3.35 Ma the percentages of *Pinus* pollen drop below 50 %, suggesting a decline in pine forest coverage and a further cooling of climate (Fig. 4). This cooling culminates around 3.3 Ma which is evident from the high relative abundance of *Sphagnum* spores, reflecting a spread of peat lands and high precipitation (Fig. 8). Additionally, the absence of temperate pollen taxa, e.g. *Carpinus*, *Carya*, *Sciadopitys* and *Tsuga*, is indicative of the predominance of boreal forest. The proportion of *Sphagnum* spores is about twice as high around 3.3 Ma than in the surface sample, suggesting a more extensive distribution of peat lands.

The upper limit of well-developed peat land communities is presently reached in the lower alpine zone which upper limit ranges from 600 to up to 1400 m where the Scandinavian mountains reach a sufficient height (Moen, 1987, 1999). The clear boreal to alpine character of the vegetation around 3.3 Ma points towards climatic conditions cold enough to allow for the establishment of mountain glaciers in northern Norway. The cooling event at ca. 3.3 Ma coincides with glacial MIS M2, a major global glaciation event. In the Northern Hemisphere a modern-like ice configuration is suggested for MIS M2 (De Schepper et al., 2014). However, the possibility of a hiatus in ODP Hole 642B over the most extreme part of MIS M2 must be considered (see Sect. 3.2).

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At Lake El'gygytgyn a further increase in herbs and spores combined with a decrease in tree taxa is observed at 3.352 Ma, indicating enhanced cooling and relatively dry climatic conditions (Andreev et al., 2014). Between 3.310 and 3.283 Ma tundra- and steppe-like vegetation dominated around the lake but tree and shrub vegetation was still present in the area. A high *Sphagnum* content also points to the existence of wetlands around the lake (Andreev et al., 2014). In the lake Baikal region, cool climatic conditions still persisted around 3.3 Ma (Demske et al., 2002).

5.5 Vegetation and climate at 3.29–3.16 Ma

After 3.29 Ma, cool temperate deciduous to mixed forests re-migrated to northern Norway as shown by the frequent presence of pollen from temperate deciduous taxa (e.g. *Carpinus*, *Carya*, *Pterocarya*, *Quercus*) and the increase in the relative abundance of conifer pollen (Fig. 4). Between 3.29 and 3.26 Ma, pollen percentages of *Pinus* and conifers are high while those of *Sphagnum* spores are relatively low, suggesting a spread of forest at the expense of peat lands and thus warmer climatic conditions. A reestablishment of *Pinus-Larix-Picea* forests after MIS M2 is also documented at Lake El'gygytgyn and mixed coniferous forests spread in the Lake Baikal region (Andreev et al., 2014; Demske et al., 2002).

In the pollen record of ODP Hole 642B an opening of the vegetation is seen at ca. 3.26 Ma, when the relative abundance of *Pinus* pollen and *Lycopodium* spores decreases. The correspondingly increased proportion of *Sphagnum* spores suggests wetter and possibly also cooler climatic conditions (Fig. 4). Thereafter, percentages of *Pinus* increase until ca. 3.18 Ma, suggesting a spread of forests and repeated warmer phases. Diversity according to the Shannon index is higher on average between 3.26 and 3.18 Ma when compared to the preceding cool intervals (3.47–3.29 Ma) which might be indicative of the warmest climatic conditions within the Piacenzian record (Fig. 6). The decline in the relative abundance of *Pinus* pollen and marked increase in the proportion of *Sphagnum* spores after 3.18 Ma suggest the establishment of cooler climatic conditions similar to those during MIS M2. In the north-eastern Russian Arc-

tic an opening of the vegetation and drier climatic conditions is inferred from the high amounts of herb pollen in the Lake El'gygytyn record between ca. 3.25 and 3.20 Ma (Andreev et al., 2014), coinciding with low *Pinus* pollen and high *Sphagnum* spore percentages in the sediments of ODP Hole 642B. Cooler climate conditions are also recorded in the Lake Baikal region during this interval (Demske et al., 2002). In northern Norway climate oscillated between cooler and warmer phases. The high abundance of *Pinus* pollen in the sediments of ODP Hole 642B around 3.20–3.18 Ma coincides with a re-establishment of forests around Lake El'gygytyn at ca. 3.20 Ma (Andreev et al., 2014).

Over the entire 3.29–3.16 Ma interval, a spread of cool temperate montane forests in northern Norway during warmer phases is indicated by peaks in the abundances of *Sciadopitys* and *Tsuga* pollen, coinciding with high *Pinus* pollen contents (Fig. 4). Warmth-loving pollen taxa like *Carpinus*, *Carya*, *Ilex*, *Pterocarya* and *Quercus* occur frequently together with other rarely represented pollen of deciduous trees (e.g. *Acer*, *Fagus*, *Juglans*, *Nyssa* and *Tilia*), pointing to the presence of nemoral to boreonemoral forests and a warm climate (Figs. 4 and 5). Relatively high numbers of *Juniperus*-type and Cupressaceae pollen suggest the prevalence of open shrub vegetation at higher altitudes throughout the interval (Bjune, 2005; Seppä and Birks, 2001). The high proportion of *Sphagnum* spores, peaks in herbs such as Asteraceae, Chenopodiaceae and Poaceae pollen and the regular occurrence of other herb pollen taxa also suggest the continuous presence of open environments (Fig. 4). The relatively high abundance of *Sphagnum* spores also points to more humid conditions than during the previous intervals.

The negative correlation of *Pinus* and *Sphagnum* pollen percentages points to distinct changes between a wider forest coverage and expansion of peat lands, presumably indicative of repeatedly warmer and cooler climatic conditions. The development of peat lands during Piacenzian intervals that show a similar-to-present vegetation distribution and climate might have contributed to the long-term decline in atmospheric CO₂ concentrations towards the Pleistocene (e.g. Lunt et al., 2008; Martínez-Botí et al.,

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2015; Pound et al., 2015). At present circumarctic peat lands in the Northern Hemisphere form a major carbon sink (e.g. Gajewski et al., 2001; MacDonald et al., 2006). In addition, a change from a taiga to tundra dominated vegetation configuration significantly increases surface albedo by expanding snow cover over the summer (Koenig et al., 2011 and references therein). The spread in peat lands in northern Norway during the Piacenzian might have acted as a positive internal feedback mechanisms that facilitated the development of an extensive Scandinavian ice sheet around 2.72 Ma (Kleiven et al., 2002).

Our findings corroborate a previous palynological analysis of nine samples from the Piacenzian section of ODP Hole 642C, indicating the presence of a mixed conifer-hardwood forest at the northern limits of the deciduous forest zone in Norway between ca. 3.3 and 3.1 Ma (Willard, 1994). However, our high resolution study indicates that the warmth of the Piacenzian was not as stable as previously thought, but was instead interrupted by cooler intervals, causing latitudinal and altitudinal shifts of the boundary between the deciduous and boreal forest zone.

5.6 Vegetation and climate at 3.16–3.14 Ma

Climate of Norway cooled further as indicated by the steady decrease in the relative abundance of *Pinus* pollen, high proportions of *Sphagnum* spores and the sporadic occurrence of pollen from temperate taxa between ca. 3.16 and 3.14 Ma (Figs. 4 and 8). The pollen assemblage shows a strong resemblance to that during MIS M2, suggesting similar or slightly colder climatic conditions when compared to today and potentially creating conditions favourable for glacier built-up at high altitudes. Cool climate prevails in the James Bay Lowland, Canada between ca. 3.11 and 3.04 Ma as indicated by the prevalence of boreal forests (Gao et al., 2012). A thinning of forests and deflection to cooler conditions is also observed at Lake Baikal at ca. 3.18 and 3.15 Ma (Demske et al., 2002). In contrast, conifer forests grew under relatively warm climate conditions until 3.06 Ma in the Lake El'gygytyn area (Andreev et al., 2014).

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5.7 Late Pliocene climate reconstruction

Palaeoclimate estimates based on the Coexistence Approach (CA) suggest that MATs ranged between 3.7 and 15.8°C in Norway during the Piacenzian and thus were 4.2–16.3°C higher than present. The potential warming of CMTs amounts to winter temperatures 0.5–12.6°C higher when compared to today. WMTs show a clear warming with values 6–14.5°C higher than present. A minimum increase of MATs of ~ 4°C compares well with climate conditions found in southern Norway today. However, WMTs average 12°C in southern Norway at present while minimum values of ~ 16°C are inferred for the Piacenzian, suggesting Piacenzian climatic conditions that are comparable to the modern-day climate of southern Sweden. The average MAP levels of ~ 1500 mm that are reconstructed for the warmer-than-present intervals compare well to the upper range of modern values. MAP is estimated to average ~ 700 mm during the cooler, more similar-to-present intervals (Figs. 6 and 7). A prolonged decline in MAP between 3.42 and 3.35 Ma coincides with high abundances in Asteraceae pollen, supporting the interpretation of drier climatic conditions (Fig. 6, Sect. 5.3).

The application of the CA to the Piacenzian pollen assemblages of ODP Hole 642B clearly reveals a warmer-than-present climate but several factors hamper the reconstruction of narrow ranges for palaeoclimate parameters and the detection of smaller climatic changes. The prolonged colder phase between ca. 3.47–3.31 Ma that is inferred from pollen assemblage changes is not seen in the climate reconstructions because of wide and overlapping coexistence intervals (Fig. 7), which in turn result from the wide climatic tolerances of taxa. The quantification of temperature and rainfall using the CA is further hampered by the fact that the vegetation of Norway does not only change along a latitudinal gradient but also with increasing altitude of the Scandinavian mountains resulting in the regular occurrence of most common taxa in almost all samples. These limitations especially apply to marine sediment cores as a consequence of their wider pollen source area.

5.8 (Sub)Arctic vegetation evolution during the Piacenzian

During the Cenozoic, temperate to boreal forests showed a wide distribution in the Northern Hemisphere and were very uniform in their floristic composition (e.g. Wen, 1999; Xing et al., 2015). Palaeogeographic and palaeoclimatic changes during the Pliocene and Pleistocene led to today's disjunct distribution of tree genera in Europe, Asia and North America (e.g. Svenning, 2003; Xing et al., 2015). The Piacenzian flora of northern Norway exhibits a similar composition to that in Canada and Siberia at that time (e.g. Andreev et al., 2014; Pound et al., 2015; de Vernal and Mudie, 1989). The reconstructed Piacenzian vegetation and climate changes in northern Norway are closely correlated with other vegetation records across the Northern Hemisphere (Table 1), indicating a hemispheric response to external and internal forcing. Vegetation changes at Lake El'gygytgyn strongly follow orbitally-induced glacial–interglacial cycles (Andreev et al., 2014; Brigham-Grette et al., 2013). For instance, the hemisphere-wide cooling at ca. 3.48–3.47 Ma and ca. 3.3 Ma coincide with MIS MG6 and M2, respectively (Andreev et al., 2014; Brigham-Grette et al., 2013; Lisiecki and Raymo, 2005).

The circum-arctic distribution of tundra/peat lands developed during the late Piacenzian and throughout the glacial–interglacial cycles of the Pleistocene (e.g. Andreev et al., 2014; Gajewski et al., 2001). The transition of high-latitude vegetation changes from forest to tundra environments during the late Piacenzian presumably amplified the cooling through vegetation-snow albedo feedbacks (e.g. Gallimore and Kutzbach, 1996; Koenig et al., 2011). The long-term cooling trend over the Piacenzian that is observed in all records is in accordance with declining atmospheric CO₂ values from the Piacenzian towards the early Pleistocene (Bartoli et al., 2011; Martínez-Botí et al., 2015; Seki et al., 2010). Expansion of tundra biomes may have contributed to the draw-down of atmospheric CO₂, further enhancing cooling.

The main vegetation and climate changes during the Piacenzian recorded in (sub)Arctic records are illustrated in Table 1. During the earliest Piacenzian diverse forest communities persisted under a warmer-than-present climate in northern Nor-

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way, the north-eastern Russian Arctic and southern East Siberia (Andreev et al., 2014; Demske et al., 2002). In all regions cooling around 3.48–3.47 Ma is indicated by the development of open habitats. Till deposits in the James Bay Lowland, Canada provide evidence for glaciations between 3.6 and 3.4 Ma (Gao et al., 2012). A further opening of the vegetation and deterioration of climate is observed both in northern Norway and the north-eastern Russian Arctic after 3.35 Ma, culminating in the coldest recorded climatic conditions around 3.3 Ma. High *Sphagnum* spore contents in ODP Hole 642B and the Lake El'gygytyn record are indicative of an extensive distribution of peat lands during the coldest interval (Andreev et al., 2014). Warm climatic conditions re-establish after ca. 3.29 Ma in northern Norway, the north-eastern Russian Arctic and southern East Siberian which are interrupted by cooler intervals until ca. 3.16 Ma (Andreev et al., 2014; Demske et al., 2002). However, conifer forests prevail under relatively warm climatic conditions in the vicinity of Lake El'gygytyn until 3.06 Ma. Piacenzian deposits from the Yukon Territory, Canada have been assigned to the mPWP and reveal the prevalence of diverse forests with wetlands/lakes (Pound et al., 2015). Between 3.16 and 3.14 Ma reduced forest coverage in northern Norway and in the Lake Baikal area and the predominance of boreal forest in the James Bay Lowland are indicative of cool climatic conditions (Demske et al., 2002; Gao et al., 2012).

6 Conclusion

The Piacenzian high-resolution pollen record from ODP Hole 642B in the Norwegian Sea reveals repeated fluctuation of cool temperate and boreal conditions during a time interval that has previously been regarded as relatively stable. Warmest month temperatures are estimated to be 6–14.5 °C higher than present with mean annual precipitation levels similar to today. The northern boundary of the boreonemoral to nemoral forest zone was shifted northward by at least 4–8° latitude during warmer-than-present intervals. Throughout the Piacenzian record (ca. 3.60–3.14 Ma) three main climatic phases are observed:

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- 3.60–3.47 Ma: Cool temperate deciduous to mixed forest prevailed in northern Norway, suggesting a northward shift of vegetation boundaries of at least 4–8° latitude.
- 3.47–3.29 Ma: A southward shift of vegetation zones as well as a displacement of vegetation belts to lower altitudes indicates cooling. Low alpine environments develop in mountainous areas, suggesting climatic conditions similar to today. The cooling culminates at ca. 3.3 Ma (around MIS M2), potentially creating conditions cold enough for glacier built-up at the highest summits.
- 3.29–3.14 Ma: re-establishment of warmer-than-present climate conditions is indicated by re-migration of deciduous to mixed forest to northern Norway. Repeated warmer and colder phases are recorded until ca. 3.18 Ma after which climate continuously cools and conditions similar to MIS M2 establish again. The development of peat lands might have contributed to the drawdown of atmospheric CO₂ before the start of NHG.

Future studies will focus on comprehensive multi-proxy analyses of ODP Hole 642B. By combining data from terrestrial and marine palynomorphs with SST estimates based on alkenones, and oxygen and carbonate isotopes these studies will further improve our understanding of the link between terrestrial and marine changes and the mechanisms causing Piacenzian climate changes in the Nordic Seas region.

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Table 1. Summary of Piacenzian (sub)Arctic vegetation records. Time intervals correspond to the main pollen zones delimited in ODP Hole 642B (this study). Piacenzian vegetation changes are compiled from the Lake El'gygytgyn record in the NE Russian Arctic (Andreev et al., 2014); Lake Baikal record in SE Siberia (Demske et al., 2002); Yukon, NW Canada (Pound et al., 2015) and James Bay Lowland, SE Canada (Gao et al., 2012). Description of temperature and precipitation is relative and division of time intervals is arbitrary, indicating fluctuating climatic conditions.

Location/time interval	3.6–3.47 Ma	3.47–3.35 Ma	3.35–3.29 Ma	3.29–3.16 Ma	3.16–3.14 Ma
Northern Norway (ODP Hole 642B, 67° N)	Cool temperate to deciduous forest	Boreal forest and low alpine environments	Boreal forest and extensive peat lands	Cool temperate to boreal forests, long-term expansion of peat lands	Further decrease of forest coverage and spread of peat lands
Temperature	Warm	Cool	Cool	Warm	Cool
Precipitation	High	Low	High	High	High
North-eastern Arctic (Lake El'gygytgyn, 67° N)	Diverse coniferous forest with temperate trees and shrubs and peat lands	3.48 Ma: decrease in thermophilic taxa; 3.48–3.42 Ma: predominance of boreal forest and open habitats, repeated wetter and drier intervals; 3.42–3.39 Ma: boreal forest; After 3.39 Ma: boreal forest and first appearance of tundra	After 3.35 Ma: further opening of the vegetation; 3.31–3.28 Ma: mostly treeless tundra- and steppe-like vegetation with forest patches and peat lands	3.28–3.25 Ma: boreal forest; 3.25–3.20 Ma: boreal forest with open habitats; 3.20 Ma: boreal forest	After 3.06 Ma: opening of the vegetation
Temperature	Warm		Warm	Warm	Warm
Precipitation	Low	High	High	High	High
South-eastern Siberia (Lake Baikal, 53° N)	Mixed coniferous forests	At 3.47, 3.43 and 3.39 Ma: thinning of forest and predominance of boreal vegetation	After 3.3 Ma: spread of coniferous forest	At 3.26 and 3.18 Ma: thinning of boreal forest and spread of boreal taxa	After 3.15 Ma: reduced forest coverage and development of open habitats
Temperature	Warm	Cool	Warm	Cool	Cool
Precipitation	High	Low	High	Low	Low
Canada (Yukon, 64° N and James Bay Lowland, 52° N)		James Bay Lowland: till deposits dated to 3.5 Ma (3.4–3.6 Ma)		Yukon: diverse boreal forest with wetlands/lakes	James Bay Lowland: boreal forest
Temperature		Cool		Warm	
Precipitation				High	

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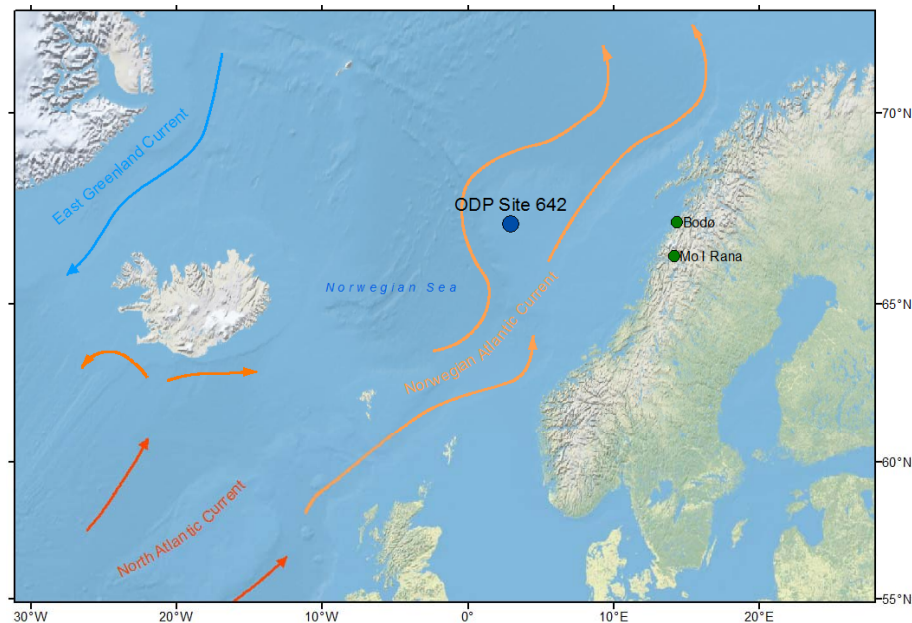


Figure 1. Location of ODP Site 642 in the Norwegian Sea. Meteorological station used for present-day climate data are located in Bodø and Mo i Rana in northern Norway. Colour coding indicates the relative temperature of currents, red = warm; orange = moderately warm; blue = cold.

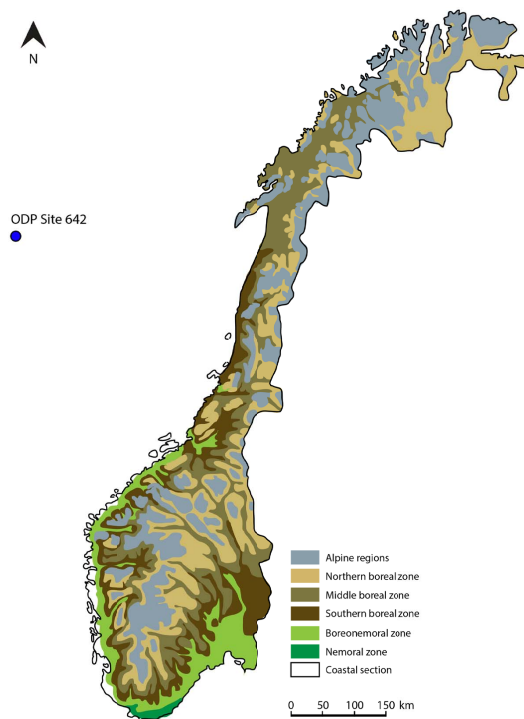


Figure 2. Vegetation map of Norway modified after Moen (1987). Position of ODP Site 642 was drawn according to scale.

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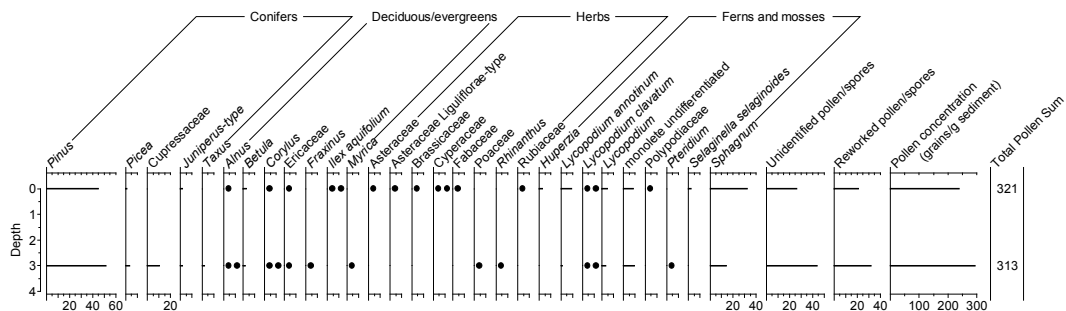


Figure 3. Pollen assemblages in the two modern (sub)surface samples from ODP Hole 642B. Black circle is representative of a single pollen grain. Percentages of pollen and spores were calculated based on the pollen sum, excluding *Pinus*, unidentified and reworked pollen/spores. *Pinus* was included in the pollen sum to calculate percentages of *Pinus*. The total pollen sum shown here comprises *Pinus* and unidentified pollen. Depth is given in centimeters.

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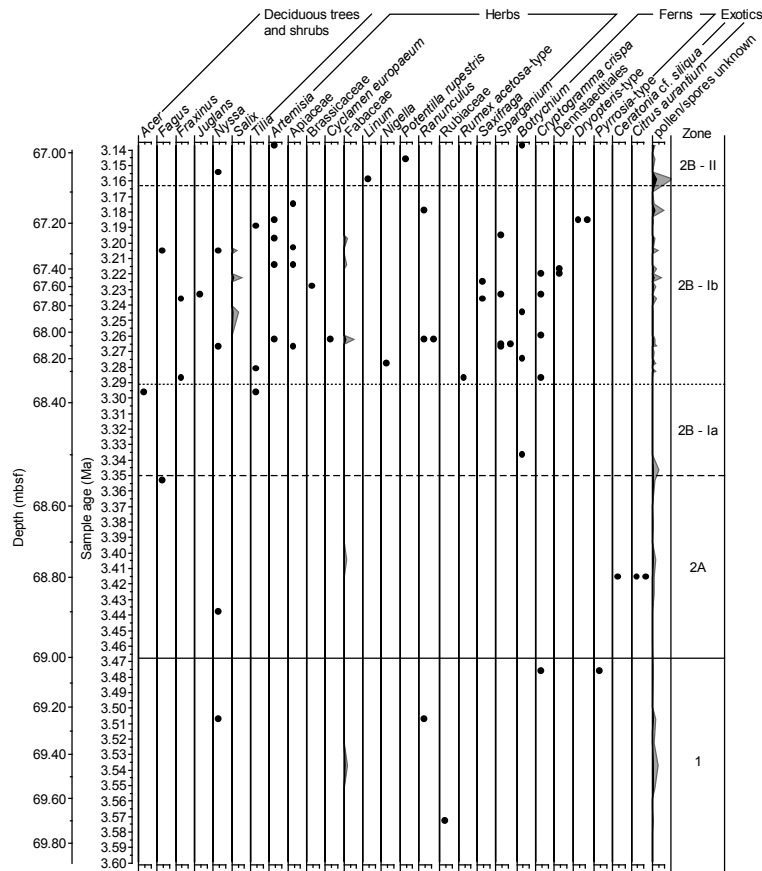


Figure 5. Pollen diagram showing taxa that occur in five or less samples. Grey area represents five times exaggeration. The exotic group marks taxa that have likely been transported to the site from the south. Depth is indicated in meters below sea floor (m b.s.f.).

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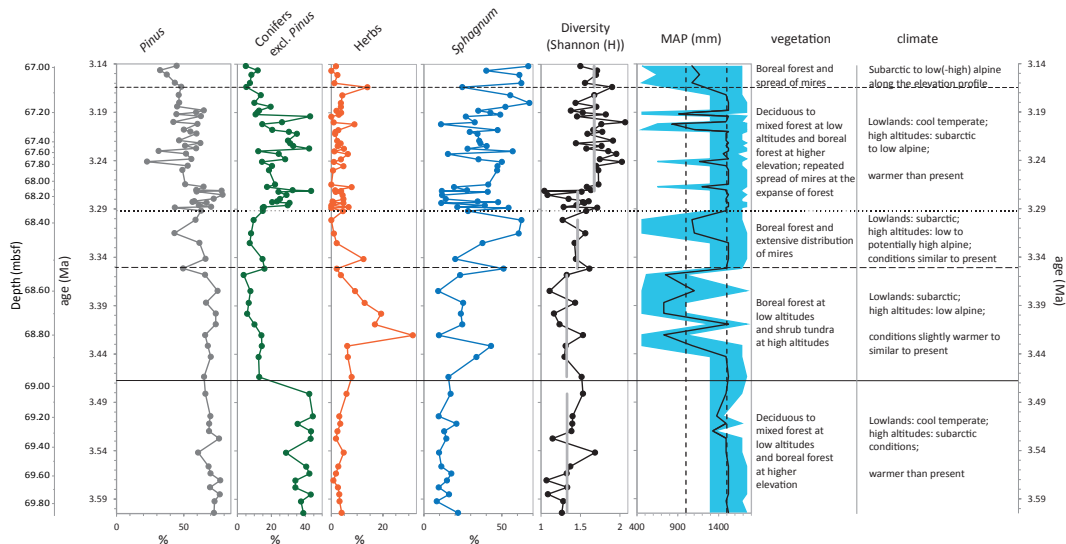


Figure 6. Summary diagram illustrating percentage changes of the main taxa/taxa groups, diversity based on the Shannon index, reconstructed mean annual precipitation (MAP) and description of the main vegetation configuration and climatic conditions. The vertical grey lines in the diversity graphs correspond to the average value across the interval. Modern MAP values are represented by the vertical dashed lines and equal 1000 and 1500 mm, respectively (Diekmann, 1994). The solid and dashed horizontal lines correspond to the main pollen zones shown in Fig. 4.

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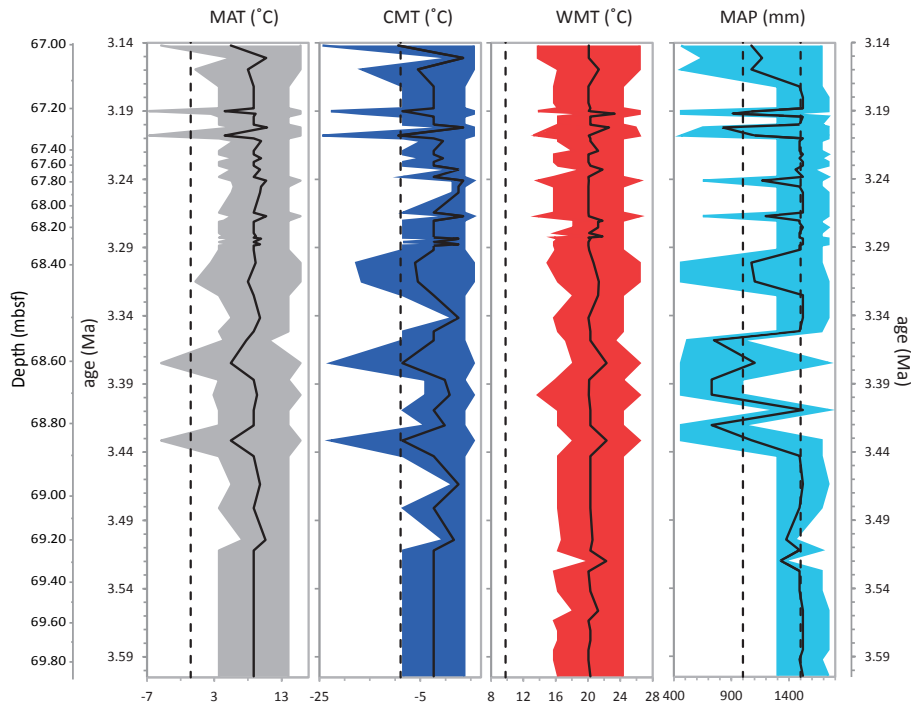


Figure 7. Climate reconstruction for Mean Annual Temperature (MAT), Coldest Month Temperature (CMT), Warmest Month Temperature (WMT) and Mean Annual Precipitation (MAP) using the Coexistence Approach. Dotted lines represent modern climate data that has been taken from the meteorological station in Bodø and Mo i Rana (see Fig. 1 for location): MAT = $-0,5^{\circ}\text{C}$, CMT = -8.9°C and WMT = 9.8°C (Norwegian Meteorological Institute and Norwegian Broadcasting Corporation, 2014). Values for MAP (1000 and 1500 mm) have been taken from Diekmann (1994).