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Holocene palaeoclimate reconstructions at Vanndalsvatnet, western Norway, with particular reference to the 8200 cal. yr BP event

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Abstract: Analyses of organic content, magnetic susceptibility, grain size and pollen in sediments from the proglacial lake Vanndalsvatnet in western Norway provide a high-resolution terrestrial record and pollen-based quantitative estimates of mean July and January temperatures and annual precipitation across the ~8200 cal. yr BP event. Glaciers in the catchment melted away at approximately 8600 cal. yr BP. Immediately following deglaciation, a series of thin minerogenic layers indicate several abrupt, short-lived glacial episodes peaking at ~8550, 8450, 8350, 8250, 8200, 7900, 7300 and 7150 cal. yr BP. A single, mid-Holocene glacial episode occurred at 4900–4800 cal. yr BP. Between 2000 and 1400 cal. yr BP, six short-lived glacial episodes occurred ~2000, 1900, 1800, 1700, 1600, and 1500 cal. yr BP. The part of Spørteggbreen that drains to Vanndalsvatnet has existed continuously since ~1400 cal. yr BP. Just prior to a first loss-on-ignition minimum reflecting a glacial episode centred at 8200 cal. yr BP, pollen-inferred July temperatures were relatively high, January temperatures were low, and annual precipitation was relatively low. During the period 8200–7900 cal. yr BP, July temperatures showed a falling trend. Both January temperature and annual precipitation, however, were relatively high. After 7900 cal. yr BP, July temperatures increased, but both January temperatures and annual precipitation were lower than in the preceding period. The pollen analytical and sedimentary data suggest that the glacial advance during the Finse event seems not to have been a response to cooler summers, but to milder winters and increasing precipitation (similar to a positive North Atlantic Oscillation weather mode).

Key words: 8200 cal. yr BP event, Finse event, lake sediments, western Norway, pollen–climate relationships, Holocene.

Introduction

Discussions of global climate change in the past, present and future tend to focus on temperature. In contrast, changes in the water cycle (precipitation, evaporation and runoff) (Stocker and Raible, 2005) and the role of seasonality in abrupt climate change (Denton *et al.*, 2005) have received little attention. Sedimentary archives contain information about climate change over decadal to millennial timescales. Recent work has demonstrated that glaciers react very sensitively to changes in climate, mainly winter precipitation and summer temperature (Dyurgerov, 2003), and that these changes are reflected in downstream lake records (eg, Ohlendorf *et al.*, 1997). In addition, robust numerical approaches are now available that allow quantitative climate reconstructions from floral and faunal assemblages in lake sediments (eg, Birks, 2003).

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Holocene marine and terrestrial records from the North Atlantic region generally show a high degree of consistency, indicating strong links between the atmospheric and marine mean climate states in the North Atlantic region throughout the Holocene (eg, Mayewski *et al*., 2004; Nesje *et al*., 2005). Holocene climate records reconstructed from marine and terrestrial proxies indicate that the Holocene climate, at least in this region, was not as stable as previously suggested from the GRIP (Johnsen *et al*., 1997), GISP2 (Stuiver *et al*., 1995) and NorthGRIP (North Greenland Ice Core Project Members, 2004) Greenland ice-core records. In particular, the early Holocene was punctuated by several prominent and abrupt climatic deteriorations. Several cooling events were superimposed upon the general warming trend that took place between the termination of the Younger Dryas and approximately 8000 cal. yr BP; the Preboreal Oscillation (PBO) at 11 300–11 150 (Björck *et al*., 1997), at Folgefonna recorded as a glacier episode (Jondal event 1; Bakke *et al*., 2005a), Jondal event 2 at 10 550–10 450 (Bakke *et al*., 2005a), the Erdalen event 10 300–9700 cal. yr BP (Nesje *et al*., 1991; Björck *et al*., 2001; Dahl *et al*., 2002) and the 8200 cal. yr BP event (Alley *et al*., 1997; Alley and Ágústsdóttir, 2005; Rohling and Pälike, 2005), termed the Finse event in southern Norway (Dahl and Nesje, 1994, 1996; Nesje *et al*., 2000, 2001) and the Miser cold oscillation in Alpine pollen diagrams (Wick and Tinner, 1997). The climate event centred around 8200 cal. yr BP was the most prominent event after the Younger Dryas that has been detected in a number of biological and physical proxies (eg, Alley and Ágústsdóttir, 2005; Rohling and Pälike, 2005). The '8.2 ka event' is marked by a brief (~80 yr) cold interval in Greenland at about 8200 years ago. The oxygen isotope dip in Greenland ice cores suggests a 5°C cooling, and a thinning of the annual layers suggests a drop in snowfall. An increase in sodium chloride content suggests the expansion of sea-ice cover in the Norwegian Sea, and a reduction in methane content of the trapped air suggests a drying of wetlands.

Here, we present a detailed study of organic content, magnetic susceptibility, grain size and pollen from a sediment core retrieved from the proglacial lake Vanndalsvatnet in western Norway, in order to provide a high-resolution terrestrial record of glacial variations and quantitative estimates of July and January temperature and annual precipitation estimates across the 8200 cal. yr BP event.

Study area

Vanndalsvatnet (1045 m a.s.l.) is located in the upper part of Vanndalen, an eastern tributary to Jostedalen (Figure 1). The lake is 0.17 km^2 and its total drainage area is approximately 5 km^2. The eastern part of the drainage area is covered by 0.6 km^2 of Spørteggbreen, a plateau glacier with an area of 28.1 km^2 (Østrem *et al*., 1988). The glaciation threshold at Spørteggbreen is close to 1720–1730 m, whereas the equilibrium-line altitude, according to the accumulation area ratio (AAR) of 0.6, is approximately 1540 m. Marginal moraines and vegetation distribution around Spørteggbreen show that the glacier covered an area of 38 km^2 during the 'Little Ice Age' maximum, which is 36% larger than at present (Nesje *et al*., 1991). The distance between the present glacier front and Vanndalsvatnet is 1.5 km, with an altitudinal difference of 365 m. In the western end of the lake there is a series of lateral moraines formed by the valley glacier occupying Jostedalen at the end of the last deglaciation (Vorren, 1973). In the valley slope between the lake and the terminus of Spørteggbreen marginal moraines (down to 1060 m) are present, interpreted to represent the Erdalen event moraines (Nesje *et al*., 1991). In front of Nigardsbreen a similar set of moraines has been radiocarbon dated from a distal peat deposit to 10 050 and 9700 cal. yr BP (Dahl *et al*., 2002). Vanndalsvatnet consists of two basins, both approximately 10 m deep, separated by a 7.5-m deep sill. In the late winter of 1986, three cores were retrieved from the distal basin with a percussion corer with 110 mm diameter sampling tubes (Nesje *et al*., 1991; Nesje, 1992). The lithostratigraphy of the three cores (cores 86-5, 86-7, 86-8) was consistent, and the core nearest the inlet was used for radiocarbon dating. In the autumn of 2001, two additional 110-mm diameter cores (cores 01-1 and 01-2) were retrieved from the proximal and distal part of the distal basin. In addition, a 65-mm modified Kajak corer (Renberg, 1991) was used to sample the uppermost sediments overlapping with core 01-2 from the distal part of the distal basin.

Methodology

Samples for loss-on-ignition (LOI) from core 01-2 were dried overnight at 105°C in ceramic crucibles before the dry weight was measured (normally 1–3 g). The water content was calculated as percent of the sediment dry weight. The samples were subjected to gradually rising temperatures for half an hour and ignited at 550°C for 1 h in a furnace. The crucibles were then put into a desiccator to cool for approximately 30 min and weighed at room temperature. The weight loss-on-ignition was calculated as percent of sediment dry weight. Wet and dry bulk density (g/cm^{-3}) was calculated from volumetric samples extracted by a syringe from the core.

Magnetic susceptibility was carried out at 0.5 mm intervals on the cleaned core face of the sediment core. The magnetic susceptibility measurements (10^{-6} SI) were carried out by a Bartington MS2B sensor.

To analyse the grain-size distribution, a Micromeretics Sedigraph 5100 Particle Size Analysis System was used (Sedigraph 5100, 1993). Together with the Sedigraph 5100, a MasterTech 51 Automatic Sampling Device was used, enabling 18 samples to be run consecutively (MasterTech 51, 1993). Approximately 1–2 cm^3 of sediment from each analysed layer was wet sieved through a 125 µm mesh using a 0.05% calgon deflocculation solution ($(NaPO_3)_6$) and stored overnight in *c*. 70 ml of calgon solution. The analyses were run on a high-speed program with an analytical measuring window ranging from 1 to 63 µm (clay to coarse silt). The data were processed using GRADISTAT (Blott and Pye, 2001) to calculate the grain-size distribution and its statistical components.

Sediment samples for pollen analysis were taken from every dark and light band of the lower part of the core. Thirty samples were analysed for their pollen and spore content from *c*. 8800 to *c*. 7300 cal. yr BP. The samples were prepared with standard KOH, HF and acetolysis treatment (Fægri and Iversen, 1989). Equally spaced traverses across the slides were counted to a total land pollen and spore sum between 800 and 1000. Identification of pollen and spores were made using keys in Fægri and Iversen (1989) and Moore *et al*. (1991) and the modern reference collections in the Department of Biology, University of Bergen. Pollen and spore nomenclature mainly follows Fægri and Iversen (1989) and Moore *et al*. (1991). The pollen diagram was drawn using the TILIA and TILIA.GRAPH programs (Grimm, 1990) showing the major pollen and spores as percentages of the total land pollen and spores.

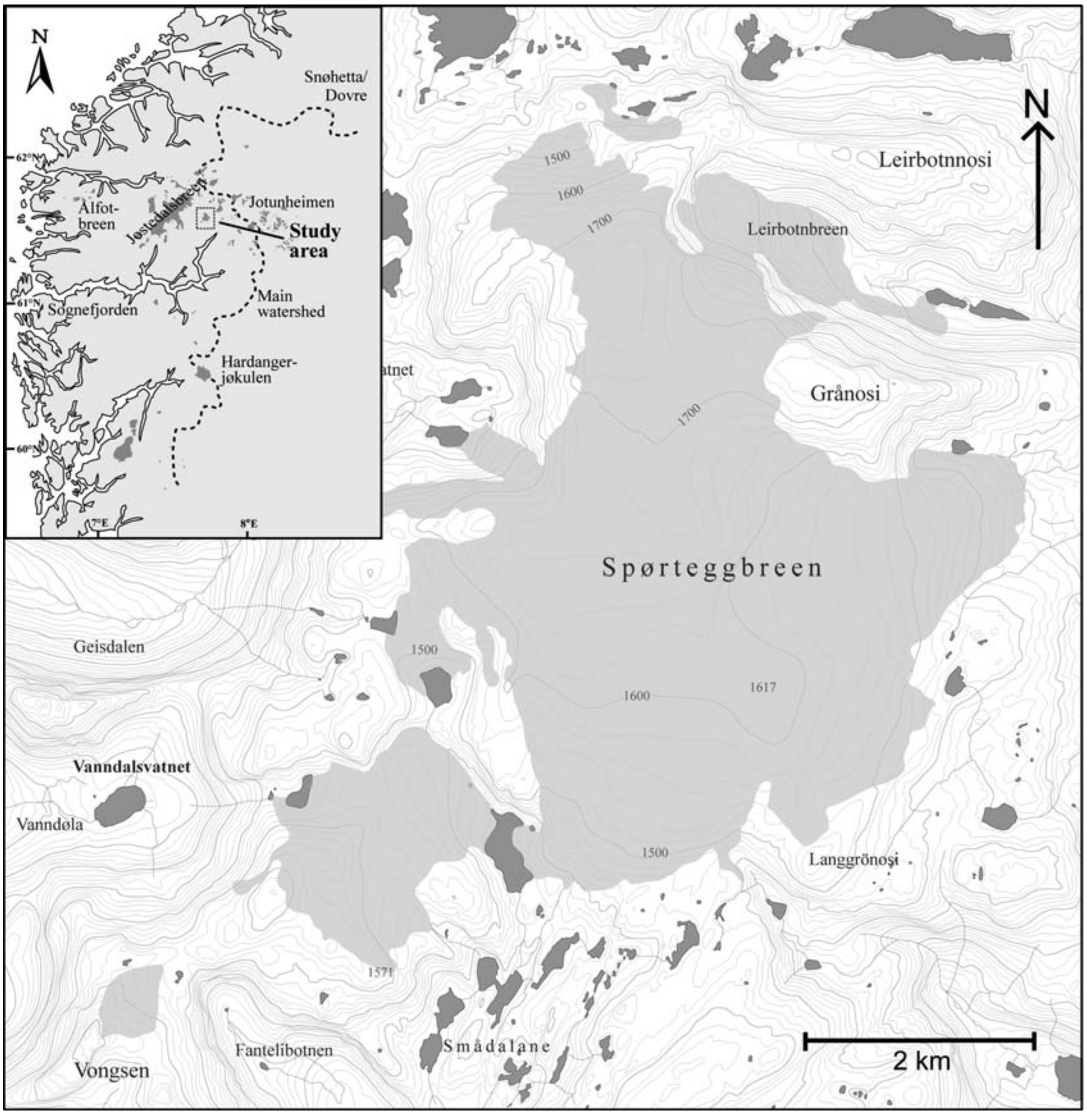

Figure 1 The Spørteggbreen glacier with its proglacial lake Vanndalsvatnet from which sediment cores have been retrieved. The location of the study area within southern Norway is shown on the inset map. Contour interval 20 m

The computer program ZONE 1.2 (Juggins, 1991) was used to detect major changes in the pollen assemblages, and the broken-stick model was used to detect which zones are statistically significant (Bennett, 1996). Principal component analysis was used to summarize the major stratigraphical patterns in the pollen data (Birks and Gordon, 1985). The PCA was performed on square-root transformed percentage data. Sample scores plotted in Figure 7 are based on Euclidean distance biplot scaling (ter Braak, 1994).

Modern pollen–climate transfer functions for mean July and January temperatures and annual precipitation were developed using weighted averaging partial least squares regression (WA-PLS) (ter Braak and Juggins, 1993; ter Braak *et al*., 1993, Birks, 1995; ter Braak, 1995) and a 191 modern surface-sediment pollen–climate data set from Norway and northern Sweden (Bigler *et al*., 2002; Birks and Seppä, 2004). Two-component WA-PLS models were used throughout because these give low prediction errors and low maximum bias when assessed in leave-one-out cross-validation (Birks and Seppä, 2004). The prediction errors are, when expressed as a percentage of the climate gradient sampled, 11.8% (July), 7.7% (January) and 14.2% (annual precipitation). The modern and fossil pollen percentages were transformed to square roots prior to WA-PLS to stabilize the variances in the data.

Lithostratigraphy

Core 01-2 was used for detailed sediment analyses (Figure 2). The basal part of the core consists of a diamicton interpreted as a till. This unit is overlain by silt with isolated clasts (dropstones). This unit is interpreted as an ice proximal deposit. Above, there is a unit of clayey silt, interpreted as a distal glaciolacustrine sediment. Above there is a 78-cm thick silty gyttja. At 138 cm and in the lower part of this unit, there are several minerogenic layers interpreted to represent short-lived glacial episodes in a period characterized by small glaciers or even an absence of glaciers in the catchment. Between 110 and 51 cm, there is gyttja silt with moss layers and thin minerogenic layers. The minerogenic layers are interpreted to represent shorter periods when glaciers were present in the catchment. The upper 51 cm consists of gyttja silt, indicating that glaciers were continuously present in the catchment. A sand layer within this unit may represent a flood layer, possibly representing the December 1743 river flood,

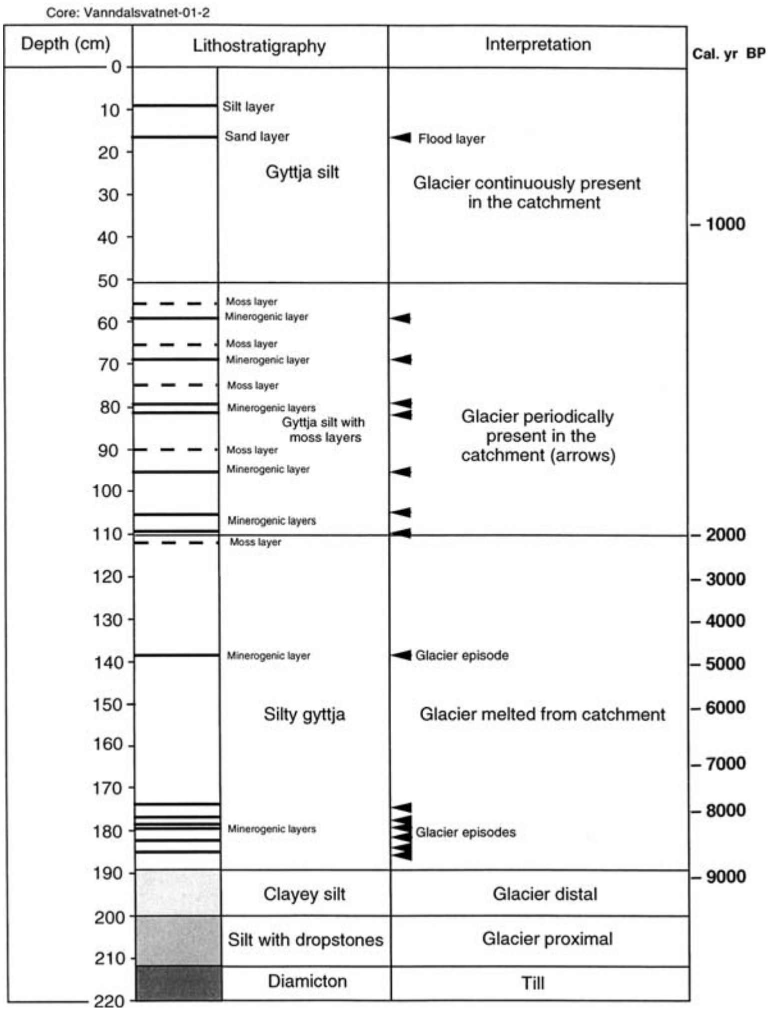

Figure 2 Lithostratigraphy and interpretation of the sediments in core Vanndalsvatnet 01-2. Approximate calendar ages BP are indicated to the right

which is the largest river flood reported in western Norway (eg, Grove, 1988).

Age/depth relationships of cores Vanndalsvatnet 01-1 and 01-2

Based on correlations of the loss-on-ignition (LOI) records between the radiocarbon-dated (ten dates; eight 'conventional' and two AMS on bulk material) core 86-8 (for details, see Nesje *et al.*, 1991) and core 01-2 ('fixed points' in Figure 3, upper panel) and the LOI correlation between core 01-2 and 01-1, age/depth curves for cores 01-1 and 01-2 were constructed (Figure 3, lower panel). A significant change in the sedimentation rate occurs at ~115 cm in the two cores, probably reflecting the initiation of Neoglaciation in the Vanndalsvatnet catchment at ~2000 cal. yr BP (Figure 2). The likely time resolution in the different segments of the two cores is indicated in Figure 3.

The lower sequence of the Vanndalsvatnet sediments

Sediment parameters

As stated above, the lower part of cores 01-1 and 01-2 shows a series of light minerogenic bands in a sequence of silty gyttja (Figure 4) that are clearly recorded in the LOI records from the two cores and other sediment parameters as measured in core 01-2 (Figure 5). The LOI minima date to ~8550, 8450, 8350, 8250, 8200, 7900, 7750, 7420, 7300 and 7150 cal. yr BP, of which the two most significant LOI minima date to 8200 and 7900 cal. yr BP. These are also characterized by relatively high magnetic susceptibility, and high dry weight, high bulk density, but no significant change in the mean grain size (Figure 5).

In southern Norway, this event was first recorded in a peat sequence at Finse and termed the Finse event (Dahl and Nesje, 1994, 1996). Similar double LOI minima have previously been recorded in five south Norwegian lakes (Nesje and Dahl, 2001), and were tentatively correlated with the 8200 cal. yr BP event recorded in the Greenland ice cores (eg, Alley *et al.*, 1997; Alley and Ágústsdóttir, 2005). In order to test whether the minerogenic-rich layers and bands in the Vanndalsvatnet record were deposited as a result of glaciers in the catchment or river floods/colluvial activity, the mean grain size and sediment sorting were plotted together (Figure 5). When the two parameters are positively correlated and in phase, the minerogenic sediments are most likely deposited from suspension in a low-energy environment. Sorting/mean anomalies (when the two parameters are in anti-phase/negatively correlated), on the other hand, most likely mean that the sediments are deposited in a high-energy environment (eg, during a river flood/colluvial episode) (eg, Bakke *et al.*, 2005b). As seen from the upper panel in Figure 6, the two parameters are in phase

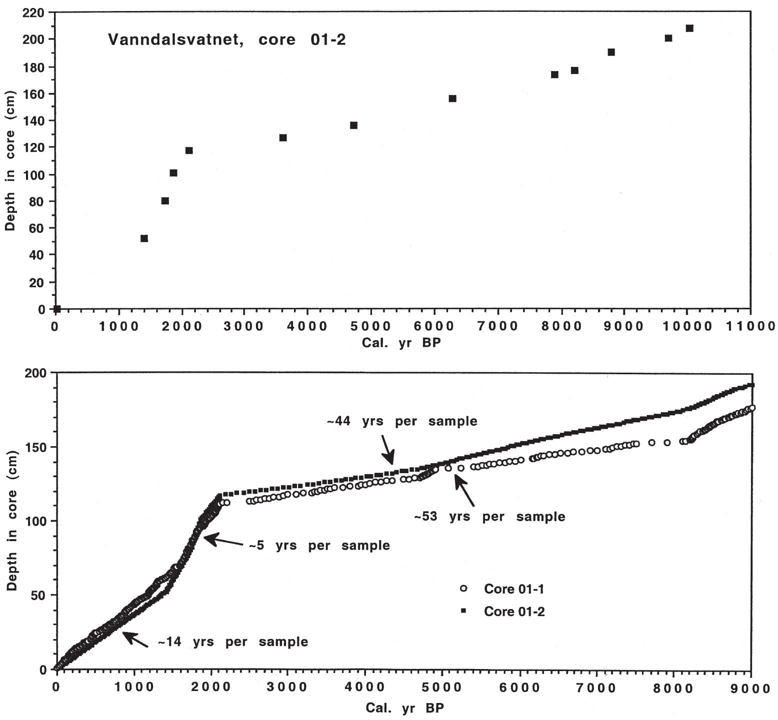

Figure 3 Upper panel: correlation ('fixed') points between core 01-2 and core 86-8 in Nesje *et al.* (1991). Lower panel: the age/depth relationship for every loss-on-ignition sample (0.5 cm contiguous intervals) in cores 01-1 and 01-2. The inferred time resolution in different segments of the two cores is indicated

throughout the entire record ($r = 0.91$) and also in the lower part of the sequence (Figure 6, lower panel).

Pollen analysis

Pollen analysis was performed in the lower part of core 01-2 to detect any changes in the local vegetation and to reconstruct January and July temperatures and annual precipitation before, during, and after the two peaked Finse-event. The 'banded' sediments gave a unique possibility to sample at close intervals and to obtain a fine temporal resolution, thereby detecting fine-scale vegetation changes resulting either from changes in temperature or precipitation, or a combination of both. Lately, focus has been on changes in the early Holocene climate (Barnett *et al.*, 2001; Seppä and Birks, 2001, 2002; Seppä *et al.*, 2002). During the period of glacial advances *c.* 8200 cal. yr BP (eg, Matthews *et al.*, 2000, Nesje and Dahl, 2001) palynological data suggest that the event may have resulted in a lower *Pinus sylvestris* tree-limit (Moe, 1979; Barnett *et al.*, 2001), whereas from eastern Jotunheimen, Gunnarsdottir (1996) found no evidence for vegetation change. In northern Finland Seppä and Birks (2001) reconstructed higher July temperatures during this time period.

Vegetation development and changes

A simplified pollen diagram for the lower part of Vanndalsvatnet core 01-2 is shown in Figure 7. Mean July (T_{jul}) and January (T_{jan}) temperatures and annual precipitation (P_{ann}) were reconstructed using all pollen and spore taxa found in the samples using two-component WA-PLS models (Birks and Seppä, 2004). The inferred climate values are given in Figure 8. Sample scores on the first principal component axis (41.6% of the total variance) when plotted stratigraphically (Birks and Gordon, 1985) show a long-term trend (Figure 7) from high to low scores, but with an absence of any trend during pollen zone VA-3. This pattern suggests that the long-term vegetational development was interrupted for about 350 years just at the time of the Finse event.

Pollen zone VA-1 – early Holocene pioneer vegetation (c. 8800–8670 cal. yr BP)

The lower pollen zone has a low pollen concentration. *Betula*, *Pinus*, Poaceae and *Dryopteris*-type are dominant. *Hippophaë rhamnoides*, *Salix herbacea*-type and *Rumex acetosa*-type occur, reflecting the early Holocene open vegetation on poorly developed soils after the ice retreat. Tree pollen present are most probably long-distance transported.

Pollen zone VA-2 – early Holocene forest establishment (c. 8670–8200 cal. yr BP)

Pinus sylvestris pollen dominates together with *Betula, Alnus,* Poaceae and Cyperaceae. Trees were probably present near the lake, and the range of herb pollen types suggests a diverse but closed vegetation.

Pollen zone VA-3 – Finse event (c. 8200–7850 cal. yr BP)

This pollen zone is characterized by increasing values of *Alnus* and *Dryopteris*-type and *Gymnocarpium dryopteris*, while *Pinus sylvestris* and *Betula* decrease. Total tree pollen decreases as fern spores increase, probably indicating more humid conditions in the area. The major herb taxa are *Rumex acetosa*-type Poaceae, *Solidago*-type, *Ranunculus acris*-type and *Potentilla*-type.

Pollen zone VA-4 – c. 7850–7240 cal. yr BP

Alnus, *Betula* and *Dryopteris*-type dominate this upper part. *Pinus sylvestris* continues to decrease, while broad-leaved trees such as *Ulmus, Quercus* and *Sorbus* increase, possibly on richer soils. The major herb taxa are as in zone VA-3. The number of pollen taxa present increases in this zone.

Reconstructed July and January temperatures, and annual precipitation

Inferred T_{jul} did not change significantly during the timespan of the analysed samples (Figure 8) given that the pollen–

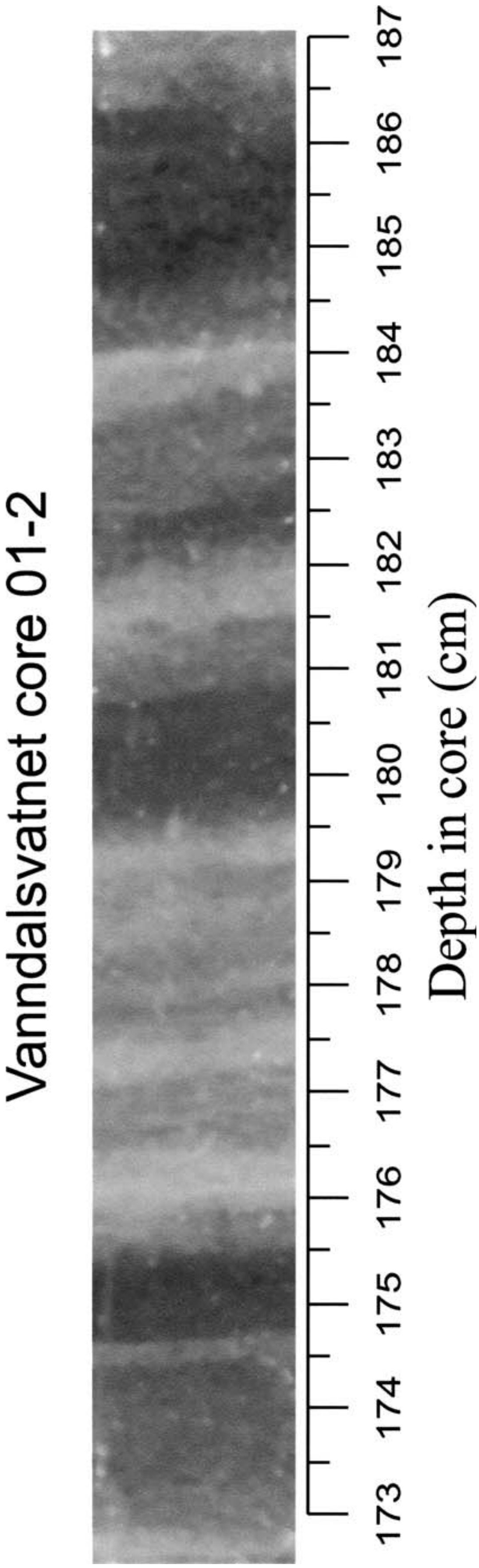

Figure 4 Photo of the lower part of core 01-2 showing the alternating minerogenic and gyttja layers in this part of the core. White spots on the image are minerogenic particles interpreted to have been deposited by snow avalanches (A. Nesje, J. Bakke, S.O. Dahl, Ø. Lie and A.-G. Bøe, unpublished data, 2006)

climate reconstructions have an inherent prediction error of about 1°C (Birks and Seppä, 2004). On average T_{jul} varies between 11.1°C and 12.5°C. More marked changes are seen in the inferred January temperature and annual precipitation in the period corresponding to pollen zone VA-3 (Finse event). Below and above this zone T_{jan} fluctuates around *c.* −5.5°C, while during zone VA-3 and the Finse event T_{jan} increases to −2.5°C. At the same time, as winters became milder, P_{ann} increased from about 1650 to 2100 mm. The model error predictions are 2.6°C for January and 418 mm for annual precipitation (Birks and Seppä, 2004), suggesting that the inferred climate values at the time of the Finse event are unlikely to be a result of chance variation associated with the inherent uncertainties in the inference models.

Immediately before the first LOI minimum at 8200 cal. yr BP, the climate was characterized by high July temperatures, low January temperatures and low annual precipitation (Figure 8). During the period between 8200 and 7900 cal. yr BP, July temperatures show a falling trend, whereas both January temperature and annual precipitation remained relatively high. After 7900 cal. yr BP, July temperatures increased and both January temperatures and annual precipitation were lower than in the preceding period.

Discussion

In Greenland, the 8200 cal. yr BP event involved a major cooling, drop in snow accumulation rate, an increase in wind-blown dust, sea salt and forest-fire downfall, and a decrease in methane (eg, Alley *et al.*, 1997). Numerous studies in Europe and the North Atlantic seem to record the occurrence of the ~8200 cal. yr BP climate event (see review by Alley and Ágústsdóttir, 2005; Rohling and Pälike, 2005; Nesje *et al.*, 2005).

In western Scandinavia, a distinctly cool but oceanic summer climate in the early Holocene was possibly due to more persistent westerly airflow that was replaced about 8000 cal. yr BP by a more meridional flow pattern and by the development of more frequent blocking anticyclonic summer conditions with a more southerly and southeasterly air flow. Inferred high summer temperatures in Scandinavia reconstructed from palaeobotanical evidence, high sea-surface temperatures, restricted glacier coverage and the presence of thermophilous molluscs around Svalbard, all indicate an early to mid-Holocene (most records indicate ~7800–6300 cal. yr BP) summer-season thermal maximum in these areas (see review by Nesje *et al.*, 2005 and references therein).

The vegetational development at Vanndalsvatnet, as reflected by the pollen diagram (Figure 7), mainly follows the same trends of development of early Preboreal vegetation seen in other studies in this region (eg, Kvamme, 1984, 1989; Nesje *et al.*, 1991). The establishment of a *Pinus* forest is preceded by a shrubby pioneer flora with *Betula*, *Salix* and a range of herbs. The first expansion of pine pollen in the area is dated to *c.* 9000 BP and a gradual increase is seen until *Pinus* reaches its maximum at *c.* 8400 cal. yr BP at several localities in the area (Kvamme, 1984, 1989; Nesje *et al.*, 1991). The pine maximum is seen in the lower part of the pollen diagram (zone VA-2) where the values exceed 40% at *c.* 8600 cal. yr BP, suggesting the local presence of *Pinus sylvestris* and a forest mixed with *Betula*. The pine–birch forest was later replaced by a mixed *Betula* and *Alnus* forest, as seen by the small increase in *Alnus* in zone VA-3 and even more in zone VA-4, with high values of *Betula*. The local expansion of

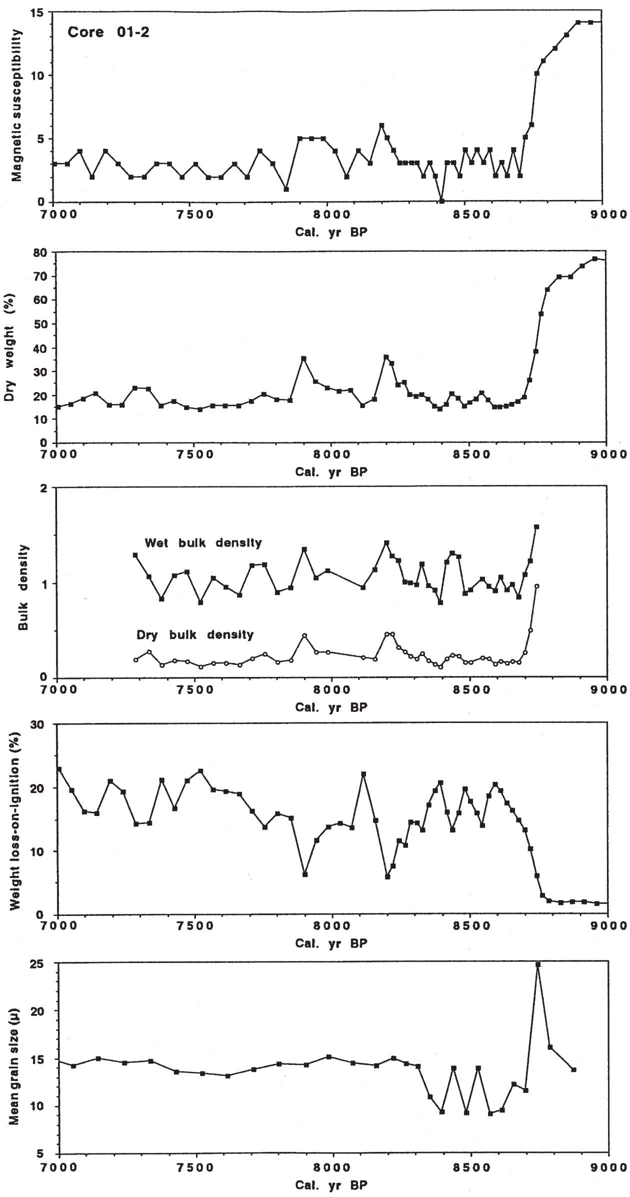

Figure 5 Magnetic susceptibility (10^{-6} SI), dry weight, wet and dry bulk density, loss-on-ignition and mean grain size in core 01-2 in the time window 9000–7000 cal. yr BP. The loss-on-ignition maxima and minima are from distinct gyttja and minerogenic layers, respectively, seen in Figure 4

Alnus is dated in the mountains of southern Norway to around 8000 cal. yr BP (Kvamme, 1992).

After the Finse event *Alnus* and *Betula* dominated the forest canopy and grasses, sedges and ferns were abundant in the field layer. Increasing pollen values of broadleaved trees are seen from this time and indicate the development of a more edaphically demanding forest on stable fertile soils and warmer summers after *c.* 7800 cal. yr BP.

The most striking changes in inferred climate are the changes in T_{jan} and P_{ann} between *c.* 8200 and 7850 cal. yr BP. Even though T_{jul} does not change significantly, the presence of *Pinus sylvestris* from *c.* 8600 cal. yr BP to *c.* 8000 cal. yr BP is consistent with a temperature 2°C higher than today in this area (Nesje and Kvamme, 1991; Nesje *et al.*, 1991; Gunnarsdottir, 1996; Torske, 1996). Subsequently pine was replaced by birch and alder woodland in wetter habitats. A decrease in the percentages of *Pinus sylvestris* and a lowering of the pine tree-limit during and after the Finse event is also found in Leirdalen, Jotunheimen (Barnett *et al.*, 2001). The effect of an increase in precipitation is seen by the increasing values of *Alnus* and of different fern spores (eg, *Dryopteris*-type, *Cryptogramma crispa* and *Gymnocarpium dryopteris)* in zone VA-3. The decrease in LOI of the sediments suggests that more soil erosion and mass movement occurred because of increased precipitation during the Finse event. Based on studies of two varved lake-sediment sequences in Sweden, Snowball *et al.* (2002) also found an increase in mineral-matter accumulation, a proxy for winter-snow accumulation, and a significant decrease in total pollen influx. During the Finse event, winter precipitation was higher than at present (Dahl and Nesje, 1996).

The results are dependent on the time resolution in the analysis and on the magnitude of the cooling (or precipitation changes) to which the vegetation responded. The amount of the biotic response is dependent on the closeness to the species distribution limit, as it is easier to see a response if the locality is at the limit of the species distribution (ecotone boundary) (Smith, 1965). The ideal species for such a purpose are species that have a short life cycle, such as *Betula* and *Corylus*, which also produce large amounts of pollen. Vegetation dynamics are closely connected with climate change and can be explained by different life-history strategies and physiological tolerances of

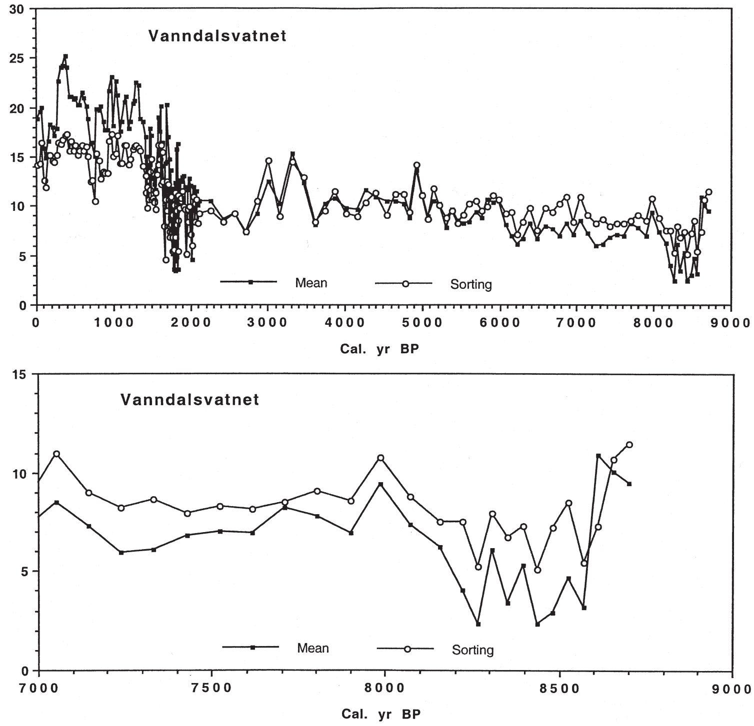

Figure 6 Mean and sorting of the minerogenic fraction in the entire (upper panel) and lower part (lower panel) of core 01-2

the species involved. Tinner and Lotter (2001) showed an immediate response in the pollen assemblage of terrestrial vegetation connected with a cooler climate at 8200 cal. yr BP in the Alps, where the most prominent change is the decrease of *Corylus* pollen by ~20% within <150 years. *Corylus* responded within 20 years to the cooling at 8200 cal. yr BP and *Pinus* and *Betula* within 40 years to the following warming. Another important factor is the locality and its climate. The reason for seeing the Finse event in Vanndalsvatnet and other localities in Jostedalen/Jotunheimen and not in northern Finland (Seppä and Birks, 2001) is possibly because Vanndalsvatnet is in a more oceanic climate.

The first LOI minimum (glacial episode) in the Vanndalsvatnet lake record, centred around 8200 cal. yr BP, is most likely equivalent to the Finse event (Dahl and Nesje, 1994, 1996) that is also recorded in a number of lake records in southern Norway (Matthews *et al.*, 2000; Nesje *et al.*, 2000, 2001; Nesje and Dahl, 2001; Seierstad *et al.*, 2002) and the oxygen isotope minimum as recorded in the Greenland ice-core records (Figure 9). The second significant LOI minimum occurred around 7900 cal. yr BP. This double LOI minimum pattern has also been detected in other proglacial sediment records in southern Norway (Matthews *et al.*, 2000, 2005; Nesje and Dahl, 2001). This second glacial episode is, however, not similarly strongly expressed in the oxygen isotope records in the GISP2 and GRIP ice core records. In the NorthGRIP record, however, this period was characterized by low oxygen isotope values (Figure 9).

Given that the abrupt 8200 cal. yr BP event may be most evident in winter-dominated proxies, and the underlying anomaly more characteristic of summer conditions, the seasonal significance of proxy records must be considered. In the Cariaco Basin, a broad multipeak low in the percentages of Ti between 8400 and 7750 cal. yr BP reflects aridity due to reduced northward migration of the Intertropical Convergence Zone during summer (Haug *et al.*, 2001). A single sharp anomaly at 8250–8100 cal. yr BP in the greyscale record reflects increased wintertime trade-wind intensity (Hughen *et al.*, 1996). A reduction in the monsoon activity during the 8200 cal. yr BP event has been recorded in a number of proxy records (see Rohling and Pälike, 2005 and references therein). The climate perturbation in the Vanndalsvatnet record lasted from ~8400–7850 cal. yr BP (~550 yr). Rohling and Pälike (2005) also noted that the anomalies related to the 8200 cal. yr BP event lasted 400–600 years in many proxy records, starting at approximately 8600 cal. yr BP. This led them to suggest a more complex nature of this climate event than has hitherto been suggested (ie, the meltwater hypothesis).

The 8200 cal. yr BP event has been modelled by Ágústdóttir (1998), Renssen *et al.* (2001, 2002), and Bauer *et al.* (2004). The ECBILT-CLIO coupled climate model was used by Renssen *et al.* (2001, 2002) to conduct several transient simulation experiments in which an early Holocene equilibrium climate state was perturbed by releasing freshwater pulses of different duration. ECBILT CLIO consists of an oceanic GCM, coupled to a three-layer quasi-geostrophic atmospheric model. The reduced complexity of the atmosphere in ECBILT-CLIO makes it feasible to run it in ensemble mode over thousands of years. Despite its reduced complexity, ECBILT-CLIO is able to reproduce the modern climate reasonably well, including a NAO mode of variability. One particular perturbation scenario resulted in a cooling event that was similar in duration and magnitude to the 8200 cal. yr BP event, giving support to the hypothesis of a North American meltwater source for the THC weakening. However, this does not necessarily mean that this particular scenario is the only possible realization of the system for the 8200 cal. yr BP event. Renssen *et al.* (2002) showed that the relation between the THC response and the applied freshwater forcing is highly complex. In ensemble experiments with identical freshwater pulses, the duration of the THC weakening varied widely (from 200 to over 1000 yr). Finally, the cold climate anomaly about 8200 years ago was investigated by Bauer *et al.* (2004) with CLIMBER-2, a coupled atmosphere–ocean–biosphere model of intermediate complexity. The climate model simulated a cooling of about 3.6 K over the North Atlantic induced by a meltwater pulse from Lake Agassiz routed through the Hudson Strait.

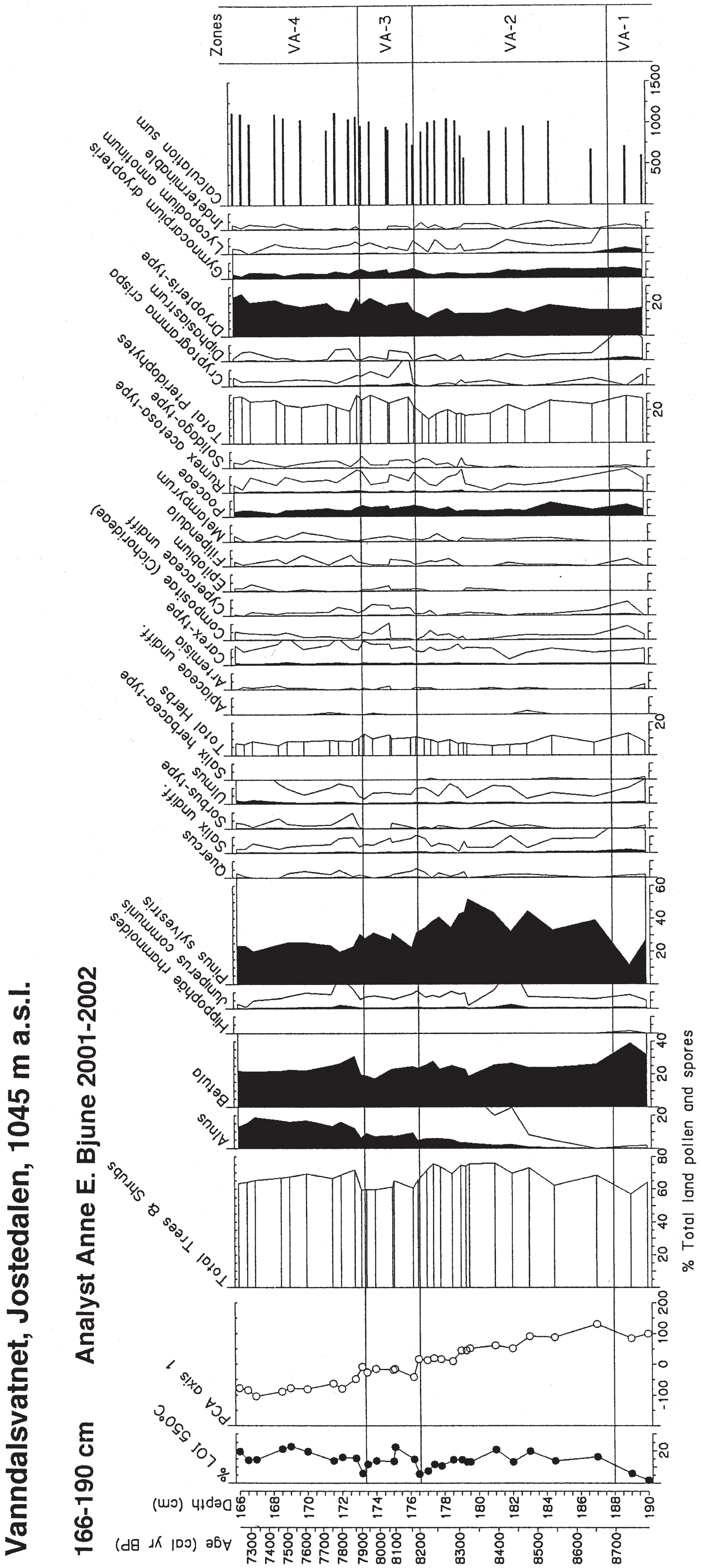

Figure 7 Pollen diagram from the lower part (166–190 cm) of core 01-2 from Vanndalsvatnet. The diagram is constructed on a depth basis; the estimated age scale is also shown. The loss-on-ignition (LOI) and the sample scores (multiplied by 100 on PCA axis (41.6% of the total variance)) are also plotted. Minor pollen and spore taxa are not shown. The original full counts are available from Anne E. Bjune or H. John B. Birks

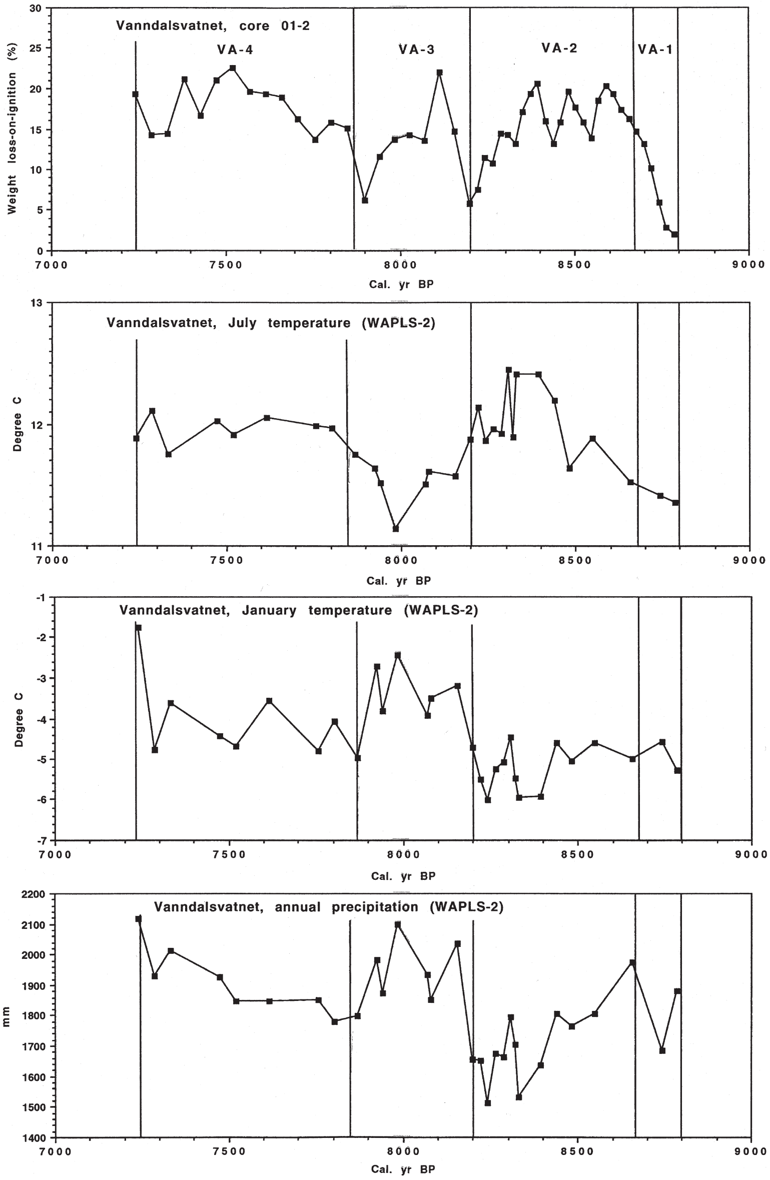

Figure 8 Loss-on-ignition and reconstructed mean July and January temperatures, and annual precipitation based on the pollen diagram in Figure 7. The pollen zones (VA-1 to VA-4) are indicated by vertical lines

Conclusions

During deglaciation, glaciers in the Vanndalsvatnet catchment had melted away at approximately 8600 cal. yr BP. Immediately following deglaciation, a series of thin minerogenic layers indicate abrupt, short-lived glacial episodes peaking at $\sim$8550, 8450, 8350, 8250, 8200, 7900, 7300 and 7150 cal. yr BP. A single, mid-Holocene glacial episode occurred at 4900–4800 cal. yr BP. Between 2000 and 1400 cal. yr BP, six short-lived glacial episodes occurred at 2000, 1900, 1800, 1700, 1600 and 1500 cal. yr BP. The part of Spørteggbreen that drains to Vanndalsvatnet has existed continuously since $\sim$1400 cal. yr BP. The sediment parameters indicate that the two most significant glacial episodes were centred at $\sim$8200 and 7900 cal. yr BP, as also recorded in Jotunheimen by Matthews *et al.* (2000, 2005).

It is not easy to see large vegetational changes during the Finse event from the pollen analytical results, probably because the locality is not on any species critical distributional border. During the early Holocene it is also difficult to separate climatic response from biotic processes. But from these data and the sediment parameters, the glacial advance during the Finse event here seems not to have been a response to cooler summers, but to milder winters and increasing precipitation.

Just before the first glacial episode at 8200 cal. yr BP, July temperatures were relatively high, January temperatures were low, and annual precipitation was relatively low. During the period 8200–7900 cal. yr BP, July temperatures generally fell. Both January temperature and annual precipitation, however, were relatively high. Subsequent to 7900 cal. yr BP, July temperatures increased and both January temperatures and annual precipitation were lower than in the preceding period. The analyses presented here suggest that the increased glacier activity at 8200 cal. yr BP was not primarily controlled by a rapid decrease in summer temperatures, but by a significant increase in winter storminess that advected large amounts of precipitation over western Norway similar to a positive North Atlantic Oscillation weather mode. The second glacial episode, however, seems to be the result of a summer cooling of *c.* 1°C. This counteracted the decrease in winter precipitation. The glacial retreat subsequent to 7900 cal. yr BP was due to higher summer temperatures in conjunction with decreased winter precipitation. The occurrence of the second glacier episode

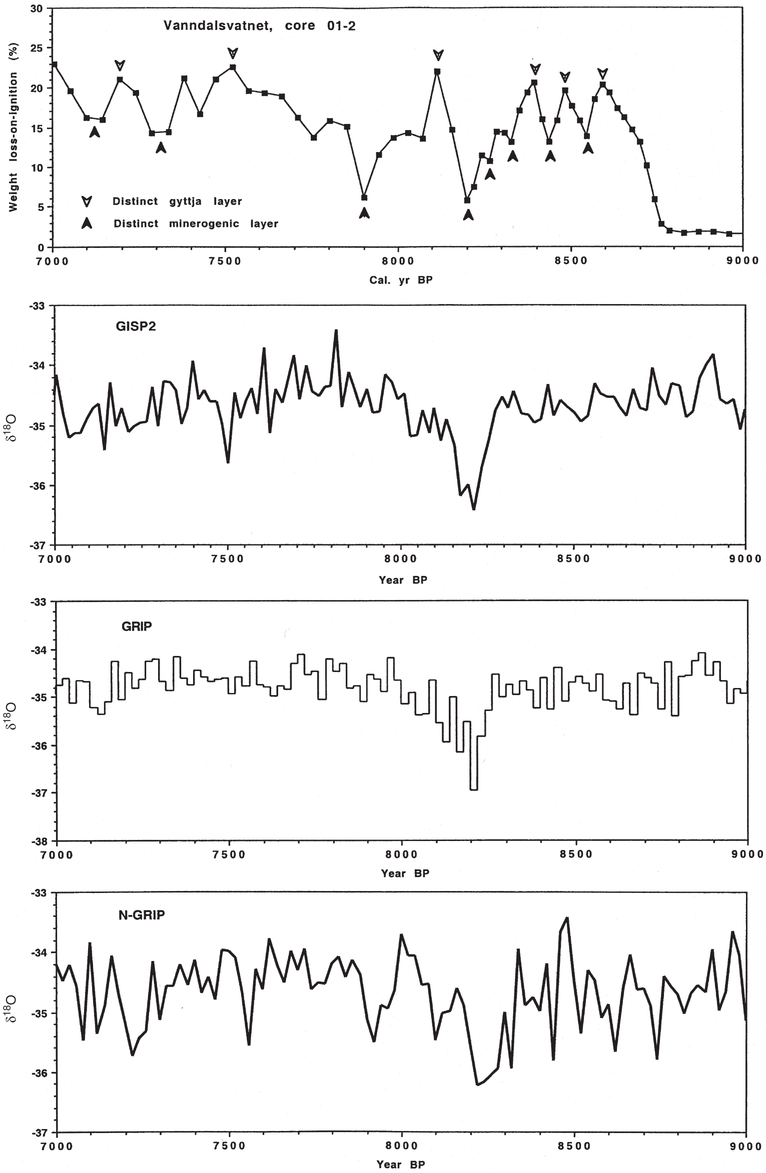

Figure 9 Loss-on-ignition in Vanndalsvatnet core 01-2 compared with the stable oxygen isotope ($\delta^{18}O$) record from the GISP2 (Stuiver *et al.*, 1995), GRIP (Johnsen *et al.*, 1997) and NGRIP (North Greenland Ice Core Project Members, 2004) Greenland ice cores between 9000 and 7000 year BP

thus gives new and interesting insights into the dynamical recovery of terrestrial environmental systems as well as the behaviour of the atmospheric system during the 8200 cal. yr BP event.

Both the pollen analytical data and the sediment parameters from Vanndalsvatnet thus suggest that the glacial advance during the Finse event here seems not to have been a response to cooler summers, but to milder winters and increasing precipitation ('positive North Atlantic Oscillation weather mode'). This is in agreement with numerous lines of evidence from studies in the circum-alpine region, indicating a phase of cooler and wetter climatic conditions interrupting a warm period.

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