Younger Dryas glaciation in the Ålfoten area, western Norway; evidence from lake sediments and marginal moraines

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During the Younger Dryas, the Ålfoten area was covered by ice caps separated from the continental Scandinavian inland ice. The local Younger Dryas glacier margins of two coalescing plateau glaciers, Ålfotbreen and Davikbreen, have been reconstructed on the basis of marginal moraines, lacustrine sediments and radiocarbon age estimates. The Younger Dryas glaciation was more extensive in this area than previously postulated. Ålfotbreen advanced to its maximum position during the early/middle Younger Dryas, before the deposition of the Vedde Ash tephra layer ca. 10,300 yr BP.

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Introduction

During the late Weichselian and early Holocene retreat of the Scandinavian inland ice front in western and central Norway, the ice sheet partly disintegrated into separate ice caps mainly due to intense and rapid calving in the fjords and submerged valleys (Reite et al. 1982; Klakegg et al. 1989; Reite 1994). Of these ice caps, the former Ålfotbreen, lasting from Bølling/Allerød until early Preboreal, was the largest and probably also the most long-lived. In addition, a number of cirque glaciers occurred in the coastal mountains beyond the inland ice margin (Reite 1968, 1994; Sollid & Sørbel 1979; Larsen & Mangerud 1981; Larsen et al. 1984; Rye et al. 1987; Nesje & Dahl 1992; Alme et al. 1994; Andersen et al. 1995b; Busengdal et al. 1995). The majority of these local glaciers also seem to have survived the Bølling-Allerød warm period (Larsen et al.1988). The position of the inland ice sheet border during Younger Dryas is shown in Fig. 1.

This paper deals with the Younger Dryas ice cap in the Ålfoten area, its geographical extension, equilibrium line altitude, dynamic behaviour and age relations. The purpose of this investigation was to reconstruct and date the Younger Dryas maximum glacier margin, and to obtain proxy data on the late glacial climate. Because of its moderate size compared to the inland ice sheet, and its coastal position with assumed high precipitation, although much less than today (Nesje & Dahl 1992), it is reasonable to assume that the ice cap was sensitive to the abrupt and significant late glacial climatic shifts (Larsen et al. 1984; Dansgaard et al. 1989; Broecker 1992; Lehman & Keigwin 1992; Lehman 1993; Taylor et al. 1993).

The study area

The Devonian bedrock area south of Nordfjorden consists of resistant sandstones and conglomerates (Fig. 1) which constitute an uneven, sloping mountain plateau rising from 600–700 m a.s.l. in the west to ca. 1400 m in the east adjacent to Hyenfjorden. The highest mountain, Gjegnen, rises to 1670 m a.s.l. at the western border of Gjegnalundsbreen. Steep cliffs and narrow, deeply incised fjords and valleys are typical morphological features in this area.

The Ålfoten and Gjegnalund glaciers have areas of 18.7 km^2 and 13.0 km^2 respectively (Østrem et al. 1988). The culmination of Ålfotbreen is 1379 m a.s.l., descending to 790 m on the southern side and 890 m on the northern side.

Gjegnalundsbreen further to the east culminates at 1440 m a.s.l., and descends to 1060 m in the south and 892 m on its northern side. In addition to these two largest ice caps, ca. 50 smaller glaciers and permanent snow fields occur in the Devonian highlands. The striking geographic overlap of the Ålfoten ice cap during the Younger Dryas and the Devonian sedimentary rocks reveal the resistance towards physical erosion and chemical weathering of these rocks (Fig. 1). The Ålfoten area has a maritime climate and the present glaciers owe their existence to high precipitation, often >4000 mm/yr (Pytte 1969).

Earlier reconstructions of the Ålfoten Younger Dryas glacier were made by Fareth (1987) and Klakegg et al. (1989). Fareth's reconstruction was based on marginal moraines, of which the moraines at Hyen and around Dauremålsvatnet (Fig. 1) in the northeastern part of the study area are especially prominent. In other areas, most of

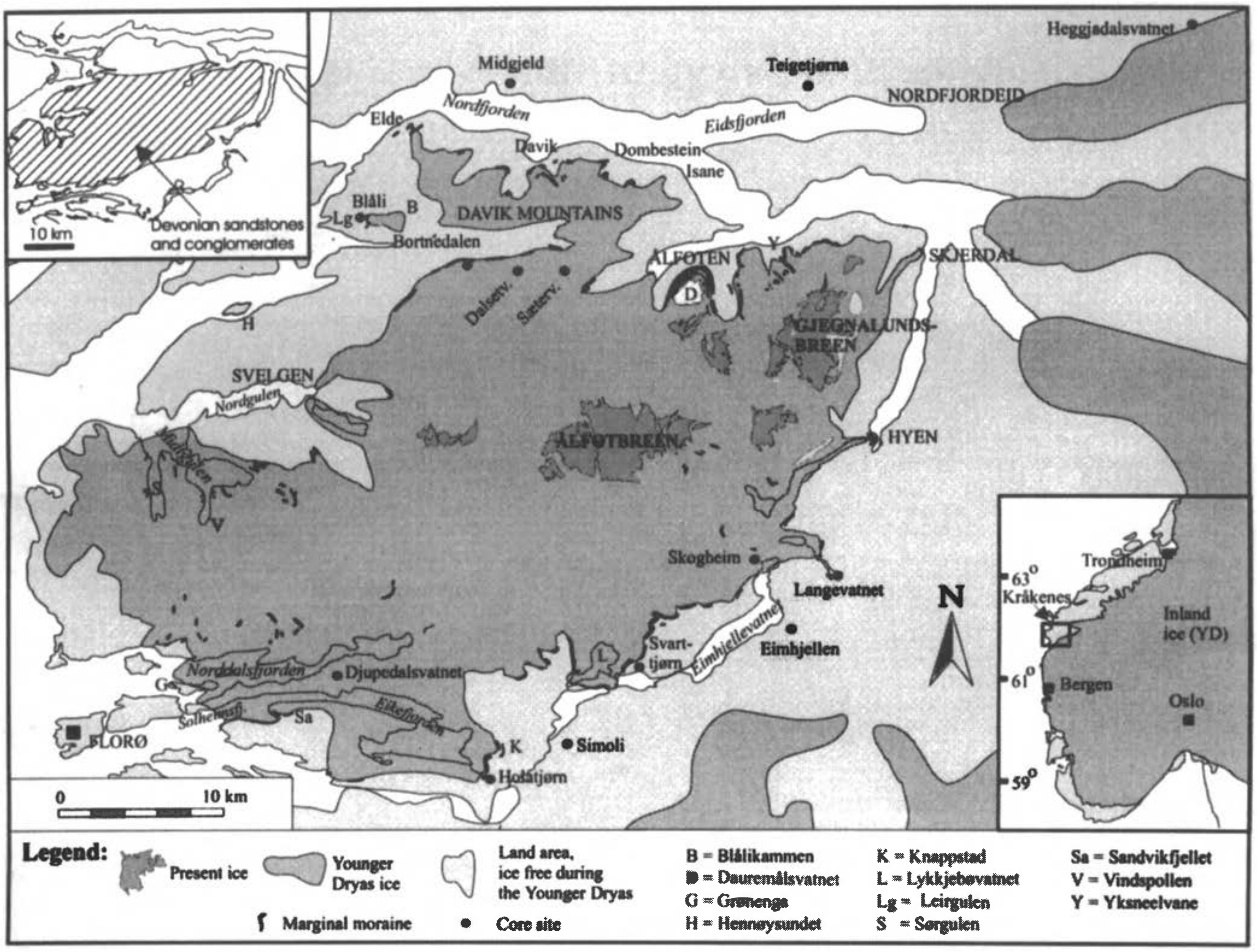

Fig. 1. Marginal moraines, Younger Dryas and present glaciation in the Ålfoten area. Core sites are marked by black dots. A key map, and a map showing the occurrence of Devonian sandstones and conclomerates are inserted.

the marginal moraines are small and discontinuous, and consequently the glacier reconstruction is more uncertain. According to Fareth (1987) and Klakegg et al. (1989) the Davik mountains to the north of the Devonian highlands were not glaciated, except for a small local glacier at Davik. According to recent studies of the Younger Dryas ELA (equilibrium line altitude) trends in the neighbouring areas of Ålfoten, a more widespread glaciation seems most reasonable. Larsen et al. (1984) suggested an ELA depression compared to the present ELA of 600–700 m in the coastal areas west of Ålfoten. To the north of Hornindalsvatnet an ELA depression of 500 m is suggested (Alme et al. 1994). With similar ELA depressions in the Ålfoten area, a rather continuous ice cover in the Davik mountains should be expected (Manseth et al. 1993).

Methods for reconstructing the Younger Dryas glaciers

Ice marginal deposits

Marginal moraines have been mapped by field work, and in some of the highest mountain areas from aerial photographs. As mentioned, the terminal moraines are especially prominent in the northeastern part of the area (Fig. 2 Fareth

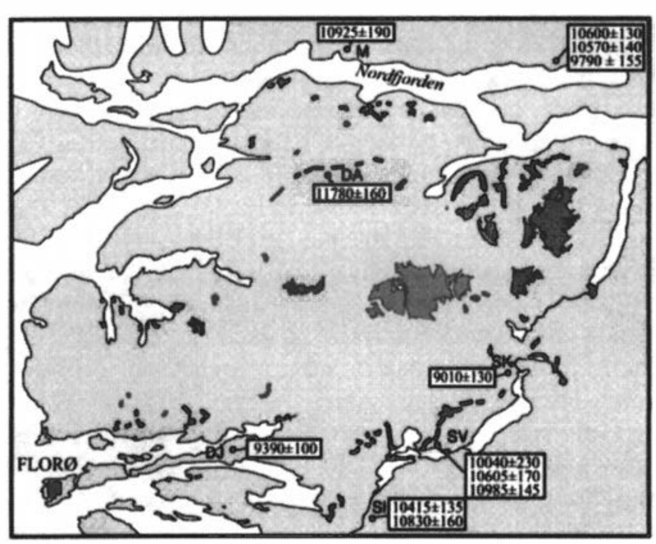

Fig. 2. Radiocarbon age estimates, terminal moraines and present glaciers (dark grey) in the Ålfoten area. M = Midgjel, T = Teigetjørna, DA = Dalsetvatn, SK = Skogheim, SV = Svarttjørn, SI = Simoli, DJ = Djupedalsvatn.

Table 1. Altitudes, areas and equilibrium-line altitudes of modern and reconstructed glaciers in the Ålfoten area.

	Highest elevation m a.s.l.	Lower glacier margin	Area (km^2)	Modern ELA m a.s.l.	Younger Dryas ELA	ELA depression
Ålfotbreen	1379 (M)	790 (M)	18.7	1186	603	583
Gjegnalundsbren	1670 (M)	892 (M)	13.0	1300	603	697
Davik mountains	1093 (YD)	100 (YD)	0 (YD: 32)	ca. 1186*	504**	682

M = modern, YD = Younger Dryas.
* Same as the Ålfotbreen glacier AAR-ELA.
** Average AAR value on the basis of a reconstructed plateau glacier with outlets.

1987). In other parts, however, the mapped marginal moraines are discontinuous, and coring has been a necessary supplement to reconstruct the areal extension of the glacier.

Lake sediments

The stratigraphy in a number of lakes and bogs, both proximal and distal to the former ice cap border, has been studied. The coring equipment used was a 110 mm modified Livingstone piston corer (Nesje et al. 1987; Nesje 1992) which was operated from a raft. The bogs were cored by a Livingstone (110 mm) or Russian (50 mm) corer. In this region the Vedde Ash tephra layer (Mangerud et al. 1984; Kvamme et al. 1989; Norddahl & Haflidason 1992; Wohlfarth et al. 1993) occurs as a distinct, and up to 40-cm-thick, black or dark-grey marker horizon in lakes which were deglaciated at that time. Consequently, the presence or absence of the Vedde Ash in lake sediments has been useful in reconstructing and dating the Younger Dryas ice margin. The Vedde Ash has age estimates of 10.3 ka BP (Bard et al. 1994; Birks et al. 1996) and 11,980 ± 80 ice core years (Grönvold et al. 1995). A few lakes which were not influenced by glacial meltwater during the Younger Dryas were cored for reference. All the radiocarbon age estimates are based on core samples (Table 2).

AAR estimates

The AAR (= accumulation area ratio)-ELA depression has been calculated as the difference between the AAR-ELA of the present Ålfotbreen and the AAR-ELA of the reconstructed Younger Dryas glacier. The calculations of the former ELA values are adjusted for land uplift. On plateau glaciers wind-transported snow is assumed to be removed from the windward side, and to accumulate on the leeward side. By using the mean ELA from the windward and leeward sides, the influence of wind on plateau glaciers can be neglected. The resulting ELA defines the TP-ELA (temperature precipitation - ELA). This TP-AAR method (= temperature precipitation–accumulation area ratio method) as described by Nesje & Dahl (1992) has been used to calculate the ELA of the present Ålfotbreen glacier, giving 1186 m a.s.l. (Manseth et al. 1993). ELA of the Younger Dryas glacier has been calculated to 603 m a.s.l., giving a depression of about 580 m. This is the mean ELA depression of the reconstructed Younger Dryas glacier.

The Davik Younger Dryas plateau glacier with short outlets is reconstructed on the basis of mostly small and discontinuous marginal moraines, and the ELA calculated. The calculated Younger Dryas ELA depression proved to be of the same order as for Ålfotbreen (Table 1).

If the glaciers are separated into specific drainage areas, there are indeed great differences in the estimated ELA, mostly due to topographic conditions. An example is the northeastern outlet glacier to Hyen which showed an ELA depression of 630 m, while the depressions in southwestern and northeastern areas (SW and NE depressions) vary from 780 m to less than 300 m respectively.

Ice margin reconstructions

The Gjegnalund–Hyen area

According to Fareth (1987), this area was covered by a continuous ice cap, from which outlet glaciers descended

Table 2. Radiometric age estimates from different localities in the Ålfoten–Nordfjord area. All the dates are corrected for a reservoir age of 440 years.

Locality	Lab. no.	Age	Analysed material	Comments
Simoli	TU-64A	10,415 ± 135	Gyttja silt/NaOH	10 cm beneath Vedde
	TU-64B	10,830 ± 160	Plant macro	
Djupedalsvatnet	TUa-67A	9,390 ± 100	Gyttja silt /NaOH	
Svarttjønna	Ua 1164	10,040 ± 230	Gyttja/insoluble fraction	
	Ua-849	10,605 ± 170	Gyttja/insoluble fraction	30 cm beneath Vedde
	Ua-850	10,985 ± 145	Gyttja/soluble fraction	
Skogheim	TUa-66A	9,010 ± 130	Gyttja silt /NaOH	
Dalsetvatnet	TUa-65A	11,780 ± 160	Gyttja silt /NaOH	
Teigetjønna	T-6550A	10,600 ± 130	Gyttja silt	10–20 cm beneath Vedde
	TUa-26A	10,570 ± 140	Gyttja	10 cm beneath Vedde
	TUa-27A	9,790 ± 155	Gyttja	28 cm beneath Vedde
Midgjeld	TUa-31A	10,925 ± 190	Gyttja	25 cm beneath Vedde

TU = Trondheim Radiocarbon Dating Laboratory, Ua = The Svedborg Laboratory, Uppsala University, NaOH = NaOH-extract.

into the surrounding valleys. Some of the glaciers extended down to sea level, allowing for the development of shorelines cut into the marginal moraines.

In the mountains above Yksneelvane, prominent moraines occur at 400 m a.s.l., which Fareth (1987) correlated with the Nor moraines of Younger Dryas age (Fig. 7). Prominent terminal moraines are located at Skjerdal and Hyen (Fig. 1). The latter is terraced at 54 m a.s.l. which, according to Fareth (op. cit.), corresponds to the Nor, i.e. late Younger Dryas, sea level. The moraines are rich in Devonian boulders, indicating glacial transport by the local Younger Dryas ice cap.

Hyen–Eikefjorden

According to Fareth (1987), lake Eimhjellevatnet (Fig. 1) was completely filled with ice during the Younger Dryas. We postulate two smaller outlet ice tongues in this area – to the north and to the west of Eimhjellevatnet respectively, because Vedde Ash layers occur in Langevatnet (341 m a.s.l.) lake sediments and at Eimhjellen, but are missing at Skogheim. Therefore the distinct 6–8 m high terminal moraine, which dams lake Langevatnet, is most likely of Younger Dryas age. Further marginal moraines on the mountain plateau 600–700 m a.s.l. west of Eimhjellevatnet mark the glacier margin in this area. Although marginal moraines are lacking in the northern part of Eimhjellevatnet, it seems reasonable to assume that the glacier tongue partly filled this lake.

Eikefjorden was filled with a glacier tongue from the northwest (Norddalsfjord area). The glacier tongue had a rather steep gradient towards the southeast in Eikefjorden and moved upvalley towards Knappstad and lake Holatjørn. The farms at Knappstad, 2 km east of Eikefjord, are located on a terminal moraine complex of Younger Dryas age. The Knappstad moraine is correlated with small, distinct marginal moraines near lake Holatjørn, 2 km further to the south (Fig. 5).

Along the southern side of Eikefjorden the reconstruction of the glacier margin is uncertain. In the narrow outlet of Eikefjorden, however, the position of a former glacier tongue can be traced in the southern slope of Sandvikfjellet; 5 km further west the glacier margin crossed Solheimsfjorden.

Norddalsfjorden–Midtgulen

A distinct marginal moraine is traceable across the island of Grønenga (Fig. 1). A continuation of this ridge has been recognized from echo soundings on the fjord bottom to the south of Grønenga.

From Norddalsfjorden to Midtgulen the position of the Younger Dryas glacier margin is more uncertain. We are not sure if the glacier in this area was connected to the Ålfoten plateau glacier. Marginal moraines indicate glacier tongues at the mouths of Sørgulen and Vindspollen (Fig. 1). These might have descended from an isolated ice cap between Norddalsfjorden and Midtgulen. According to the ELA level and the topography, a continuous ice cover probably existed.

Midtgulen–Svelgen

In this area, the marginal moraines are also discontinuous, although a more inland position is obvious, with glacier tongues descending down to Midtgulen and Nordgulen. The peninsula between Nordgulen and Midtgulen does not seem to have been glaciated during the Younger Dryas, with the exception of small local glaciers on the northern slopes, e.g. south of Hennøysundet (not shown on Fig. 1).

The northern glacier margin

Our evidence points to a larger glacier in this area than that reconstructed by Fareth (1987). We assume that the marginal moraines to the west of Ålfoten correspond to the Younger Dryas maximum, i.a. due to the absence of The Vedde Ash in the the lake sediments at Sætervatnet, Dalsetvatnet and an unnamed lake further west, proximal to these moraines (Fig. 1).

According to our reconstruction, the Younger Dryas Ålfotbreen glacier did not cross the east–west oriented mountain chain to the south of Bortnedalen, as opposed to the reconstruction made by Klakegg et al. (1989).

The Davik plateau glacier

The Davik mountains probably carried a small separate ice cap during the Younger Dryas because the central part of this mountain area lies well above the Younger Dryas ELA (Larsen et al. 1984; Klakegg & Nordahl-Olsen 1985; Fareth 1987). The Davik Younger Dryas (plateau) glacier drained in all directions. Its extent may be reconstructed by small marginal moraines. At Davik, the glacier descended almost to the sea. This was probably also the case further east at Dombestein and Isane (Fig. 1). According to the topography, the southeastern part of the Davik glacier probably coalesced with the Ålfoten ice cap. It is uncertain if the end moraine at the western end of lake Blålivatnet was built by the Davik plateau glacier or a separate cirque glacier. Northeast of this lake, 118 m a.s.l., there is a steep slope up to Blålikammen, 600 m a.s.l., leading to higher precipitation caused by the southwestern winds. Most probably, however, the Blåli lake was occupied by a small local glacier during the Younger Dryas.

Lake sediments inside the Younger Dryas ice cap margin

Although mapping of marginal moraines forms the basis of our reconstruction of the Younger Dryas Ålfotbreen ice cap, sediment cores from lakes and bogs along the former ice border have been useful and necessary for stratigraphic and dating purposes. Five core sites are assumed to lie within the Younger Dryas ice cap border, namely Sætervatnet, Dalsetvatnet and an unnamed lake to the west of Dalsetvatnet, Skogheim and Djupedalsvatnet (Fig.

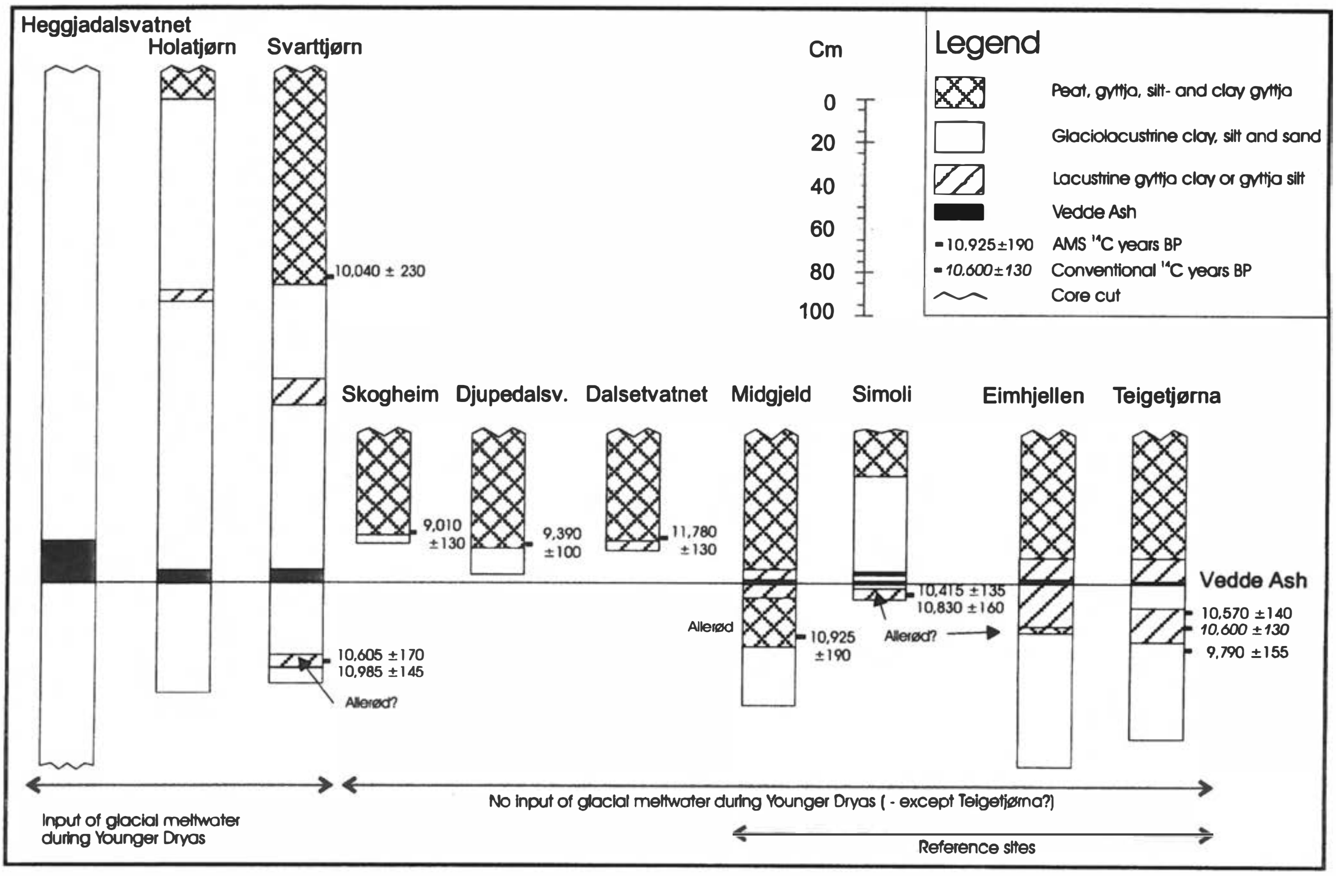

Fig. 3. Late glacial stratigraphy and radiocarbon age estimates in investigated lake sediments in the Ålfoten–Nordfjord area. The base of the Vedde Ash is used as a reference level. Only the lower parts of the Holocene peat or gyttja sequences are shown.

1). Characteristic features of all these sites are small amounts of glaciolacustrine silt and the absence of the Vedde Ash layer (Fig. 3), although abundant Vedde glass particles were found in lake Djupedalsvatn (see discussion below). The silt unit is pure minerogenic and obviously has a glaciogenic origin, deposited during the deglaciation, and differs markedly from the postglacial gyttja or peat above.

Lakes close to the northern ice margin

Lakes Sætervatnet, Dalsetvatnet and an unnamed lake 3 km to the west of Dalsetvatnet are all located proximal to the moraine ridges along the northern border of the former Ålfotbreen ice cap (Fig. 1). The westernmost lake is ca. 50 m in diameter and is situated between two subparallell moraine ridges. Its drainage area is extremely small, and no river system passes through the lake. Vedde Ash was missing in the 20-cm-thick silt bed that was recorded beneath the Holocene gyttja.

Lakes Dalsetvatnet and Sætervatnet are part of the main river system and are located ca. 1 km proximally to the marginal moraines. The coring site at Dalsetvatnet is a 5-m-deep peat bog, underlain by 10 cm silt, immediately east of the lake. Concerning the general deglaciation pattern, the radiocarbon age estimate of the silt/gyttja transition of 11,780 ± 160 BP (TUa-65A, Table 2, Figs. 2, 3) seems to be too high. This is also confirmed stratigraphically: if the basin was deglaciated in Allerød time, we would expect considerable amounts of late glacial minerogenic sediments to have been deposited, as well as Vedde Ash. Therefore, despite the dating, our opinion is that Dalsetvatnet was covered by Ålfotbreen glacier during the Younger Dryas.

The sediment core from Lake Sætervatnet, ca. 0.07 km^2, 2 km downstream from Dalsetvatnet, displayed 25 cm silt beneath gyttja. As at Dalsetvatnet, the thin silt bed and the absence of the Vedde Ash layer indicate a post Younger Dryas deglaciation.

Skogheim

Cores from a 3-m-deep tarn at Skogheim close to the nortwestern end of Eimhjellevatnet (Fig. 1) revealed a 3-cm-thick transition zone from sandy silt to silty gyttja overlain by gyttja and peat (Fig. 3). An accelerator radiocarbon age estimate on bulk gyttja from the transition zone yielded 9010 ± 130 BP (TUa-66A, Table 2, Fig. 3). The site is thought to lie proximal to the Younger Dryas ice margin.

Lake Djupedalsvatn

The small, 5–6-m-deep, circular lake Djupedalsvatnet, some 25 m in diameter and ca. 50 m a.s.l. on the 15-km-long peninsula between Eikefjorden and Norddalsfjorden is located in a topographic depression on the northern side of the local watershed (Fig. 1). Its drainage area is ca. 0.3 km^2. According to Fareth's (1987, pl. 2) palaeogeographic map, Djupedalsvatnet is thought to lie very close to the Younger Dryas ice margin. The lake is, however, situated just outside the area mapped by Fareth. From the stratigraphical record at lake Holatjørn, we conclude, however, that the Knappstad moraine is of Younger Dryas age, and consequently lake Djupedalsvatn must have been covered by ice at that time.

Cores were obtained from the peat surface and from the centre of the lake. A 20-cm-thick minerogenic sequence beneath the gyttja consists of laminated silt and some graded sand/silt layers. The base of the gyttja produced an age of 9390 ± 100 BP (Fig. 3). There is no visible Vedde Ash layer, but the silt and sand sequence, including the graded beds, contain up to 37% of volcanic glass of the Vedde type. The content of colourless, rhyolitic shards increases from ca. 60% at the bottom to almost 100% 10 cm higher up in the core. At first glance the ash content is obviously in conflict with our reconstruction of the glacier. Possible explanations may be:

1. The ash belongs to another and younger volcanic outburst, e.g. the Saksunarvatn tephra (Mangerud et al. 1986; Merkt et al. 1993; Birks et al. 1996).
2. Djupedal was deglaciated during the Vedde Ash fall, implying that our reconstruction of the Younger Dryas ice position is wrong.
3. The ash belongs to Vedde, but was temporarily stored in the glacier before redeposition in lake Djupedalsvatn.

(1) The Saksunarvatn and Vedde Ashes differ significantly. The thin glass shards of the Saksunarvatn Ash appear light brown under the binocular microscope, whereas nearly all thin shards of the Vedde Ash are colourless and more platy (Mangerud et al. 1984), as is the case in lake Djupedalsvatnet.

(2) Owing to the strong arguments for a glacier dam at Holatjørn at the time concerned (see below), we have to maintain the reconstruction implying that lake Djupedalsvatn was glaciated during the Younger Dryas.

(3) In lacustrine sediments, redeposited ash particles may occur stratigraphically above the Vedde layer. In Lerstadvatn, which was ice free in the Younger Dryas, up to 50% of the minerogenic particles in the early Holocene gyttja consist of redeposited Vedde glass (Mangerud et al. 1984; Merkt et al. 1993). At Djupedal, however, practically the whole drainage area is thought to have been covered by ice during the Vedde Ash fall. Thus, the only source left for the ash is the glacier itself. Most of the airborne glass particles that were deposited on the glacier's ablation area – except some of those that were trapped in crevasses – were washed away from the glacier surface within the first summer season and deposited outside the glacier margin. However, particles deposited above the firn limit (ELA) were buried by snow and incorporated in the glacier. Lying in the bottom of a short valley pass between Norddalsfjorden and Eikefjorden, it is reasonable to assume that meltwater drained across the peninsula at Djupedal for a short period during the retreat of the glacier. At the end of this period, but before 9390 BP, a glacial lake, which inundated the present lake Djupedalsvatnet, probably existed, allowing for the redeposition of the Vedde Ash particles.

On the basis of late glacial relative sea-level investigations and the occurrence of small traces of Vedde Ash tephra, Helle et al. (1997) suggest an earlier deglaciation of the Hardangerfjord than hitherto believed. Our assumption is that the ash particles were redeposited, after having been temporarily stored in the glacier, and the ash horizon might thus be much younger than the primary ash fall, as at Djupedalsvatnet.

Lake sediments outside the Younger Dryas ice cap margin

The lake sediments at sites beyond the Younger Dryas ice margin all contain a distinct Vedde Ash layer. The Blåli, Langevatnet, Svarttjørn and Holatjørn sites are situated just beyond postulated Younger Dryas marginal moraines (Fig. 1). At three sites, Blåli, Svarttjørn and Holatjørn, the Younger Dryas glacier readvance caused the formation of glacial lakes, the sediments of which have been identified in the lake cores, providing opportunities to obtain age estimates of the glacier maximum at these sites. The stratigraphy and ages in front of the small local glacier at Blåli indicate that the Blåli glacier maximum occurred contemporaneously with the Vedde Ash outburst. This will be discussed in a forthcoming paper on Younger Dryas cirque glaciation.

Lake Svarttjørn

During the Younger Dryas readvance a glacier lobe entered lake Lykkjebøvatnet, as documented by large marginal moraines (Figs. 1 and 4). The glacier tongue blocked the natural outlet from lake Krokstadvatnet, 60 m a.s.l. The water level temporarily rose to 102 m a.s.l., corresponding to the bedrock threshold between lake Krokstadvatnet and lake Endestadvatnet. Hence, the small lake Svarttjørn (67 m a.s.l.) north of Krokstadvatnet was inundated by the glacial lake. The sediments in lake Svarttjørn were examined in order to determine the age of the Younger Dryas glacial maximum by dating the glacial lake phase.

The surface of lake Svarttjørn and its surrounding bog is ca. 0.02 km^2. Its drainage area, 0.25 km^2, is sparsely covered with till. Based upon a series of cores taken with a Russian sampler, the most complete stratigraphy found denotes a 1.9-m-thick sequence of laminated silt, containing drop-stones, below postglacial gyttja (Fig. 3). A 6-cm-thick, distinct Vedde Ash layer occurs in the lower part of the silt unit, 50 cm above the core bottom. The same silt unit is interrupted by two zones of light brown gyttja silt,

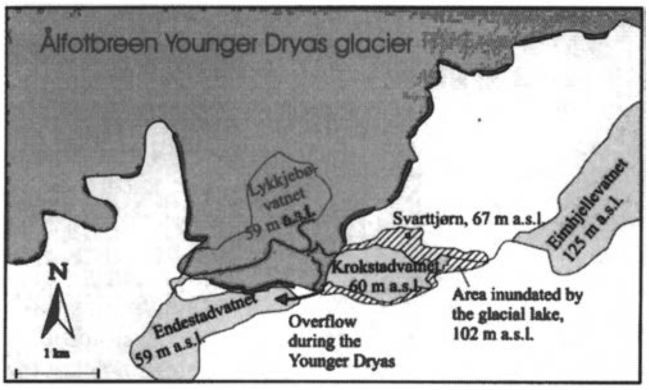

Fig. 4. Palaeogeographic map of the lake Svarttjørn area during Younger Dryas maximum. A glacier tongue from Ålfotbreen blocked the natural drainage through lake Lykkjebøvatnet forcing an overflow from lake Krokstadvatnet directly into lake Endestadvatnet.

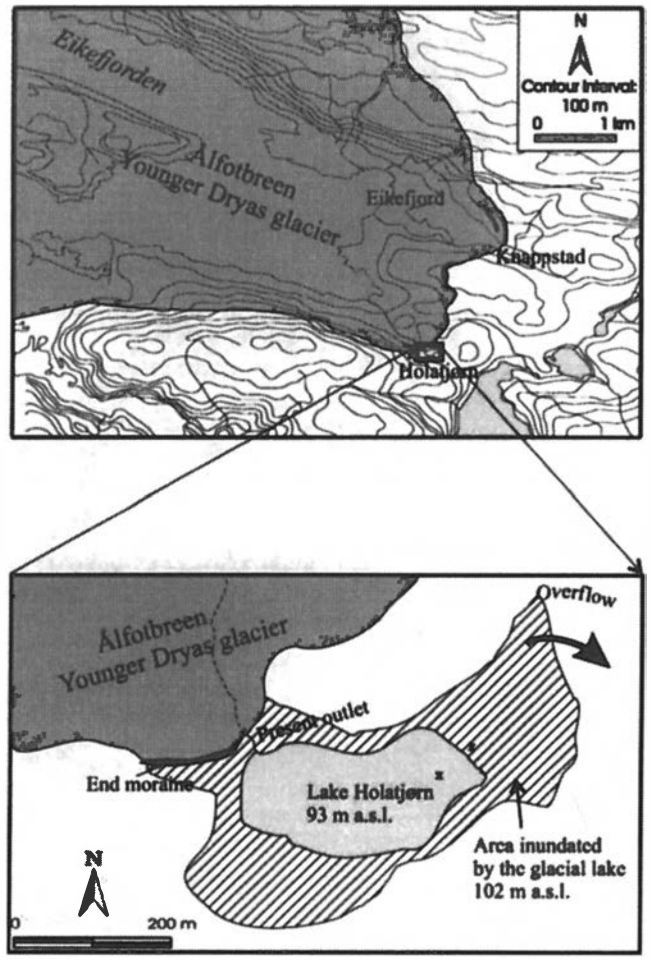

Fig. 5. Palaeogeographic map of the Eikefjord area during Younger Dryas maximum, the Knappstad moraines (black) and an enlarged map of the Holatjørn area. x = core sites.

40 cm below and 80 cm above the Vedde Ash, respectively. The laminated silt unit obviously has a glaciogenic origin, because of its pure minerogenic texture, including drop-stones, its laminated structure, and great sediment thickness. This silt unit was deposited when lake Svarttjørn was inundated by the glacial lake, enabling the input and sedimentation of glaciolacustrine silt (Fig. 4). Without glacial damming, no glacial meltwater would drain into lake Svarttjørn.

The age of the glacial lake phase is bracketed within the radiocarbon ages of 10,985 ± 145 BP (Ua-850, sol.) and 10,605 ± 170 BP (Ua-849, ins.) beneath the laminated silt and 10,040 ± 230 BP above (Fig. 3 Table 2). According to these age estimates, the advanced position of the Lykkjebøvatnet outlet glacier seems to have lasted throughout most of the Younger Dryas.

The two gyttja silt zones probably refer to periods with normal lacustrine conditions, without input of glacial meltwater, implying temporary, probably climatic induced, thinning or recession of the ice margin, and emptying of the ice lake. Owing to the short distance between the normal lake outlet and the glacier margin (Fig. 4), the ice lake might have been quite sensitive to even small glacier front oscillations. However, the gyttja silt bed close to the bottom might correspond to the Allerød Interstadial without being in conflict with the radiocarbon age estimates, accepting an Allerød/Younger Dryas climatic shift at ca. 10.8 ka BP (H. J. B. Birks pers. comm. 1997). In any case, we suggest that the boundary between the gyttja silt and the laminated silt above denotes the shift from a (normal) lacustrine phase to a glacial lake phase, corresponding to the time at which the level of the glacial lake exceeded 67 m a.s.l.

A double glacial maximum during the Younger Dryas is indicated by the upper gyttja silt bed, although we do not know to what extent, and for how long time, the ice might have receded.

If a uniform sedimentation rate in lake Svarttjørn is postulated during the glacial lake phase, the rather low-lying stratigraphical position of the Vedde Ash indicates a glacial maximum during the mid Younger Dryas. Given a maximum estimate of the time-span represented by the glaciolacustrine silt unit above the Vedde Ash layer of 300 years (10.3 ka–10.0 ka BP), a rough estimate of the period represented by the silt below is 100 years, implying a duration of the glacial lake phase of ca. 400 years.

Lake Holatjørn

The sedimentary history of lake Holatjørn, 94 m a.s.l., during the Younger Dryas is very similar to that described from lake Svarttjørn. The lake, which is ca. 0.02 km^2, lies 2 km to the south of Eikefjord (Fig. 5). Its drainage area is ca. 0.4 km^2. At present the lake drains through a moraine ridge towards Eikefjorden. The lake is situated just beyond, i.e. to the east of, marginal moraines which are correlated to the Knappstad moraine futher north. According to their topographic position these moraines obviously have been formed by a glacier tongue advancing southeastwards upvalley from Eikefjorden, towards the western end of lake Holatjørn. The glacier blocked the natural outlet of the lake, and for some time the drainage therefore is thought to have been forced eastwards, across the threshold ca. 102 m a.s.l. A former high water level is indicated by the occurrence of laminated silt one to two metres above the present lake shore.

Two cores from the lake were taken to test this assumption. One of the two 110 mm piston core samples was taken from the peat surface at the eastern end of the lake, and the other from a raft in the open lake some 50 m from the shore (Fig. 5). A 60-cm-thick clay sequence in the latter core was very liquid and became seriously disturbed when opened. Lenses of Vedde Ash appeared in the upper part ca. 50 cm above the bottom.

The 5-m-long core taken from the peat shore contained 2.6 m (postglacial) peat and gyttja, above 2.2 m laminated silt and a 5-cm-thick Vedde Ash layer. The lowermost 15 cm of the core, just beneath the Vedde Ash, was empty. However, in Fig. 3 we have added the 50 cm laminated silt that was recorded beneath the Vedde Ash in the other core; 1.2 m above the Vedde Ash layer a 5 cm thick zone of gyttja silt occurs. The great thickness of the silt unit, its laminated structure, including the Vedde Ash, and the fact that silt sediments occur above the present lake, suggest that this unit was deposited in a glacial lake during the Younger Dryas maximum. The silt unit above the Vedde Ash consists of 110 ± 10 varve-like rhythmites, but we have no proof that they are true varves.

The stratigraphic record at lake Holatjørn confirms that the Knappstad–Holatjørn moraines were formed by an Ålfotbreen glacier lobe moving upvalley from Eikefjord. The glacier advance caused an ice dam at lake Holatjørn, and the input of great amounts of glaciolacustrine sediments, including the Vedde Ash, demonstrating that this advance occurred before the ash fall (10.3 ka BP). As in lake Svarttjørn, the thin gyttja silt bed above the Vedde Ash may reflect a temporary emptying of the ice lake.

Reference localities

Five basins were cored for reference and geochronology. Four of these had no input of glacial meltwater during the Younger Dryas, namely the localities at Eimhjellen and Simoli to the southeast of the Ålfoten ice cap and Midgjeld and Teigetjørna to the north of it (Fig. 1). Lake Heggjadalsvatnet to the east of Nordfjordeid received glacial meltwater from an inland glacier outlet.

Eimhjellen

According to Fareth (1987), Eimhjellen and lake Eimhjellevatnet were covered by the Ålfotbreen glacier during the Younger Dryas. If so the Vedde Ash layer should be missing. To check this a small peat bog at Eimhjellen, ca. 255 m a.s.l., was cored. The stratigraphy beneath 3.3 m of peat was as follows: 30 cm gyttja silt above 5 cm silt gyttja above 60 cm silt and sand (Fig. 3). A distinct Vedde Ash layer, 1 cm thick, was found in the gyttja clay, 10 cm beneath the peat. The lowermost minerogenic unit most probably was deposited during the deglaciation. The silt gyttja could be of Allerød age, judging from its stratigraphic position and relatively high organic content. The gyttja silt above, containing the Vedde Ash, demonstrates that at least this site was deglaciated before 10.3 ka BP, probably already in the (late) Allerød.

Simoli

A peat bog at Simoli is located on a small valley shoulder, 120 m a.s.l., 3 km outside the Younger Dryas terminal moraines at Knappstad (Fig. 1). The catchment area of the bog is ca. 0.25 km^2. The till cover of the surroundings is thin, and the bog basin was not influenced by glacial meltwater during the Younger Dryas. The main purpose of coring this bog was to determine the deglaciation history of the inland ice.

The stratigraphy, according to cores in the central and deepest part of the bog, consists of up to 60 cm silt and sand beneath 2.7 m gyttja and peat (Fig. 3). A thin layer of gyttja silt close to the bottom was radiocarbon dated (AMS) to 10 830 ± 160 BP (TU-64B, macrofossil) and 10,415 ± 135 BP (TU-64A, bulk, Table 2).

At 1 and 7 cm, respectively, above the organic-bearing bed close to the bottom, two grey-coloured, ash-containing sand layers occur. The two morphological ash groups – acid/transparent and alkaline/brown coloured – which are typical for Vedde Ash, occur in both sand layers. However, their relative proportions are somewhat uncommon. Usually, the Vedde Ash has an acid-dominated population (Mangerud et al. 1984; Kvamme et al. 1989). This is also the case in the lower ash layer at Simoli, with an acid ash content of 60–70%, as opposed to the upper ash layer, where, for the first time, alkaline glass particles dominate and constitute 60–70% (Kvamme 1990, pers. comm.). This upper ash layer, at least, is secondary, and the unexpected ash proportion could be due to sorting mechanisms during the resedimentation. Although the Vedde Ash should be derived from two volcanic eruptions (Katla and fajökull, Norddahl & Haflidason 1992), these outbursts were simultaneous, and do not explain the double ash layers. Vedde Ash layers containing high proportions of alkaline ash have been found in other lakes, too (Berg et al. 1994). Two Vedde Ash layers stratigraphically above each other have been observed in several basins in the northwestern part of southern Norway (i.a. Eikeland 1991; Fadnes et al. 1991; Berg et al. 1994). These are explained by subaqueous sliding.

Small, shallow lakes are more favourable than larger and deeper lakes for the production and conservation of organic material (e.g. gyttja, plant remains), i.a. due to shorter warming-up periods and less intense oxidation. Shortly after deglaciation the site at Simoli was a small lake, or tarn, maximum 3 m deep, and the organic-bearing bed beneath the ash zones may represent a climatically favourable period during the early Younger Dryas. However, as at Svarttjørn, we cannot exclude an Allerød age of the lowermost gyttja.

Midgjeld

At Midgjeld opposite Davik there is a 10-m-deep, overgrown lake basin, 110 m a.s.l. (Fig. 1). Beneath 9 m peat and gyttja the stratigraphy is 12 cm gyttja clay, including a 2-cm-thick Vedde Ash layer just above the middle, then 15–20 cm clay gyttja above 20 cm pure minerogenic, laminated silt. We interpret this as a complete late glacial sequence with Younger Dryas gyttja clay, Allerød (s.l.) clay gyttja and glaciolacustrine silt from the deglaciation of the fjord glacier. A minimum radiocarbon age estimate of the deglaciation yielded 10,925 ± 190 BP (TUa-31A, Fig. 3 Table 2).

Heggjadalsvatnet

In contrast to the other investigated lakes, lake Heggjadalsvatnet, 257 m a.s.l., 10 km east of Nordfjordeid (Fig. 1), is large, ca. 0.6 km^2, and its catchment area is as much as 20 km^2. A lateral moraine at the outlet of the lake is correlated to the Nor stage of late Younger Dryas age (Fareth 1987). At this time a temporary higher lake level attributable to ice damming occurred, as confirmed by deposits of laminated silt and sand some metres above the present shore level (Fadnes et al. 1991). A distinct 18-cm-thick Vedde Ash layer in the lower part of a 3-m-thick unit of glaciolacustrine silt and clay supports the supposed late Younger Dryas age.

Teigetjørna – and the Vardehaug stage

The small and nearly completely overgrown lake Teigetjørna, 190 m a.s.l., 8 km to the west of Nordfjordeid, is situated on the flat valley threshold between Hjelmelandsdalen and Remmedalen, and ca. 1 km to the west of the local watershed, 225 m a.s.l. (Figs. 1, 7). The drainage area is small, and the water throughput is normally very low. The stratigraphy from above is 6 m peat and gyttja, gyttja silt (ca. 10 cm), Vedde Ash (1 cm), laminated silt (5–10 cm), gyttja silt (ca. 20 cm), and laminated silt (ca. 40 cm, Fig. 3). One conventional radiocarbon age estimate on bulk gyttja silt 10–20 cm beneath the Vedde Ash layer yielded 10,600 ± 130 BP (T-6550A). Two AMS age estimates on gyttja, 10 and 30 cm beneath the Vedde layer, yielded 10,570 ± 140 BP (TUa-26A) and 9790 ± 155 BP (TUa-27A, Table 2), respectively.

The late glacial sedimentary sequence at Teigetjørna resembles that at Midgjeld except forthe laminated silt layer immediately beneath the Vedde Ash at Teigetjørna. This silt probably denotes a short period with input of glacial meltwater. Since no local glacier existed in the catchment area of this lake during the Younger Dryas, one possible explanation could be that ice masses from the fjord glacier squeezed up into the lower part of Hjelmelandsdalen during the Vardehaug readvance during the early Younger Dryas (Klakegg & Nordahl-Olsen 1985; Fareth 1987; Rye et al. 1987) and forced an overflow through the mentioned valley pass, including lake Teigetjørna, towards Remmedalen (Fig. 6). If so, the Vardehaug stage may be dated to immediately before the Vedde Ash fall, ca. 10.3 ka BP. On the basis of marine bivalves, the Vardehaug readvance has been dated to ca. 10.7 ka BP (Mangerud et al. 1979; Klakegg & Nordahl-Olsen 1985; Rye et al. 1987; Andersen et al. 1995. The age of the Vedde Ash is based on radiocarbon age estimations on terrestrial/lacustrine sediments, and if the reservoir age during Younger Dryas was 700–800 years instead of 440 years (Bard et al. 1994; Andersen et al. 1995a; Austin et al. 1995; Haflidason et al. 1995), the marine and terrestrial ages would correspond.

Another consequence of such an interpretation of the stratigraphy in Teigetjørna is that the glacier front in Eidsfjorden during the Vardehaug substage advanced further out than suggested by Fareth (1987), i.e. well beyond Naustdal (Fig. 6). There is, however, one serious objection raised against this interpretation: The mentioned Vedde Ash layer in Heggjadalsvatnet (257 m a.s.l.) 25 km further east, and close to the fjord glacier, strongly indicates that this lake was ice free *contemporaneously* with the ice-directed drainage across lake Teigetjørna, which implies that the surface gradient of the fjord glacier for some time was nearly horizontal for 25 km. Therefore we cannot exclude other explanations, for instance:

1. There is a time gap (hiatus) between the silt and the Vedde layer, and the silt might have been deposited some time before the ash fall.
2. The silt bed in lake Teigetjørna was deposited by a mudflow or an earth slide.
3. The silt unit is the sedimentary response to a climatic deterioration with extremely low organic production and severe soil erosion.
4. The ash layer in lake Heggjadalsvatnet is secondary, e.g. a result of redeposition of ash grains which had been temporary stored in the glacier.

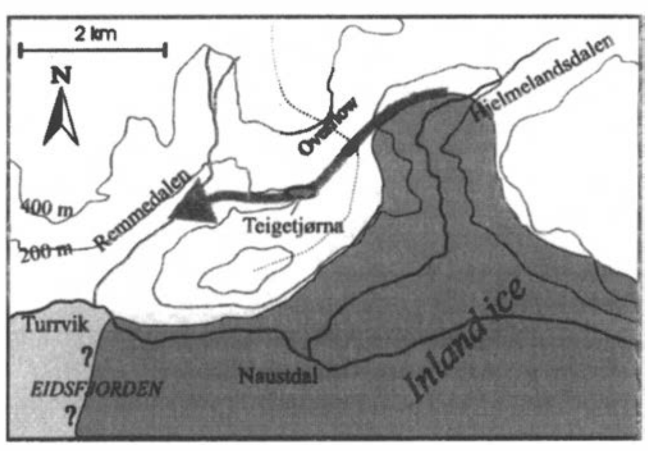

Fig. 6. Inferred ice-directed overflow through lake Teigetjørna caused by the damming effect of the fjord glacier in the lower part of Hjelmelandsdalen, 5 km to the west of Nordfjordeid, during the Younger Dryas maximum. Stippled line: local watershed.

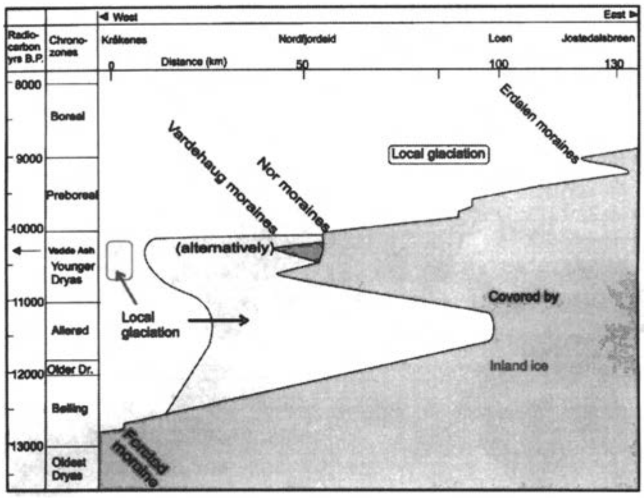

Fig. 7. Time–distance diagram for the deglaciation of Nordfjord. Simplified and revised after Mangerud et al. (1979) and Rye et al. (1987).

The following arguments can be raised against these alternative explanations:

1. Several cores have been taken within the lake basin, all with the same stratigraphy. Instead of a hiatus, we would expect the opposite, i.e. a rather high sediment input during Younger Dryas, as in the other lakes investigated.
2. The silt unit is rather uniformly laminated, and both texture and structure have little resemblance to mudflow deposits.
3. The silt bounderies are very sharp, and similar pure minerogenic sequences are missing in the other lakes which did not have input of glacial meltwater.
4. In lakes containing secondary Vedde Ash grains, e.g. lake Djupedalsvatnet, the ash zones are scarcely, or not at all, visible to the naked eye, despite the high proportion of glass. Moreover, the lower boundaries of redeposited Vedde Ash layers are expected to be diffuse, in contrast to the sharp boundary in lake Teigetjørna.

So far, we have not been able to draw any absolute conclusion concerning the age of the Vardehaug stage (Fig. 7). If the younger date (10.3 ka BP) is correct, the seemingly low gradient of the glacier surface – as well as the great glacial readvance of at least 35 km during early Younger Dryas (Klakegg & Nordahl-Olsen 1985; Fareth 1987) – might be explained by a glacial surge.

Discussion and concluding remarks

The Ålfoten–Gjegnalund area has a terrestrial relief of nearly 1000 m. It is therefore reasonable to assume that some of the steepest slopes were not ice covered during the Younger Dryas. The topography influenced the AAR-ELA depression, which was less than 300 m in the northeastern parts where the Younger Dryas glacier only descended to a mountain plateau 600–800 m a.s.l.

If we divide the Ålfoten Younger Dryas glacier into four quadrants, the major part of the Younger Dryas glacier in the northeastern quadrant descended to the mentioned mountain plateau, whereas only a minor part descended to Hyenfjorden at Skjerdal, which leads to a too small depression of the AAR-ELA compared with the mean depression of the entire Ålfotbreen glacier. In contrast, the southwestern part consisted of rather extensive, low-lying fjord glaciers, leading to a larger depression of the Younger Dryas ELA. The TP (temperature–precipitation)-AAR depression, which is the mean value of all quadrants, is 580 m. This is in accordance with results from neighbouring areas.

The Younger Dryas lacustrine sediment sequences in lakes without input of glacial meltwater are rather thin, usually less than 30–40 cm, faintly brown-coloured clay- or silt gyttja (Fig. 3). The Vedde Ash layers are distinct, and they usually vary in thickness from a few millimetres to 4–5 cm. The Younger Dryas lacustrine sediments are brownish grey, and may be distinguished from the darker and more organic-rich sediments of supposed Allerød age (e.g. Midgjeld, Eimhjellen, Simoli). Detailed investigations of the late glacial deposits at Kråkenes (Fig. 1 inset map) seem to indicate a slightly younger climatic Allerød/ Younger Dryas transition, ca. 10.8 ka BP, than usually expected (H. J. B. Birks pers. comm. 1997). Therefore the radiocarbon age estimates of this transition at Simoli (10,415 $\pm$ 135 BP, 10,830 $\pm$ 160), Midgjeld (10,925 $\pm$ 190 BP) and Teigetjørna (10,570 $\pm$ 140 BP, 9790 $\pm$ 155 BP) do not contradict an Allerød age, apart from the last date mentioned.

Lakes Svarttjørn, Holatjørn and Heggjadalsvatnet (Fig. 3) received input of glaciolacustrine silt during the Younger Dryas due to glacial damming. Here the Younger Dryas sedimentary sequences are pure minerogenic silt and clay and may be up to several metres thick. The Vedde Ash layers are generally thick, too, at Heggjadalsvatnet 18 cm, at other sites not mentioned here, up to 40 cm.

The faintly brown horizon of gyttja silt in lake Svarttjørn close to the bottom of the core (Fig. 3) is assumed to be (either Allerød or early Younger Dryas) lacustrine sediments, deposited before lake Svarttjørn was inundated by the ice dammed lake. However, we are not sure whether the content of the organic material (gyttja silt) is a temperature (i.e. Allerød s.l.) indicator, or a sedimentological (i.e. lacustrine) indicator. In the latter case the gyttja silt could be of of early Younger Dryas age. The estimated radiocarbon ages of the clay gyttja (10,605 $\pm$ 170 and 10,985 $\pm$ 145, Fig. 3 Table 2) do not exclude any of the two alternative explanations.

Radiocarbon age estimates of the Vedde Ash layer (ca. 10.3 ka BP), as well as its stratigraphical position in a great number of lake cores, including Kråkenes (Mangerud et al. 1984; Stalsberg 1995), point to an ash fall close to, or just above, mid Younger Dryas. In lakes Svarttjørn and Holatjørn the Vedde Ash layers occur in the lower part of the glaciolacustrine silt units indicating some time-lag from the climatic onset of the Younger Dryas until the maximum extension of the Ålfotbreen glacier. Assuming uniform glaciolacustrine sedimentation rates in the two lakes and an Allerød/Younger Dryas boundary at 10.8 ka BP, the time-lags might be some 300–400 years. Of the Lykkjebøvatnet and Eikefjorden outlet glaciers there are both topographic and stratigraphical arguments that the former reached its maximum first. It is, however, remarkable that the much larger glacier outlet that had to move across Eikefjorden reached its maximum almost contemporaneously, and well before the Vedde Ash fall. The expansion of the Ålfoten ice cap obviously took place in early Younger Dryas, during the time interval ca. 10.8 ka – ca. 10.4 ka BP. The great size of the ice cap and the early expansion towards its maximum position during the Younger Dryas indicate that a rather extensive Ålfoten ice cap existed during the Allerød.

The Krokstadvatn (Svarttjørn) ice lake was formed very close to the outlet glacier front, implying that the ice lake would have been sensitive to glacier oscillations. There are no signs of any glacier advances beyond the marginal moraines (Fig. 4), indicating a steady glacier front position during mid and late Younger Dryas. An early glacier expansion is in keeping with a postulated Younger Dryas climatic culmination at ca. 10.6 ka–10.5 ka BP (Wohlfarth et al. 1994) followed by warmer and/or drier conditions after ca. 10.5 ka–10.4 ka BP in southwestern Norway (Paus 1990), southern Scandinavia (Björck & Digerfeldt 1984; Björck & Möller 1987; Berglund & Rapp 1988; Lemdahl 1988) and in the Norwegian Sea (Lehman & Keigwin 1992).

We have no precise dating for the beginning of the glacial withdrawal. The minimum age estimate of the draining out of the ice-dammed lake at Krokstadvatnet, 10,040 ± 239 BP, has a rather large standard deviation. In addition the 10 k yr BP radiocarbon plateau makes dates of this age still more uncertain (Ammann & Lotter 1991; Broecker 1992; Hajdas-Skowronek 1993).

At lake Holatjørn 110 ± 10 varvelike pairs of laminae (rhythmites) could be recognized above the Vedde Ash layer. A similar number of rhythmites were found above the Vedde Ash at Kråkenes (Stalsberg 1995, p113). However, of at least 270 rhythmites within the Younger Dryas laminated silt at Kråkenes, only ca. 170 are thought to be true varves, the rest being local turbidites (Stalsberg op. cit.). Thus the number of rhythmites here is considerably less than the number of years. This is probably the case at lake Holatjørn as well, implying that the glacier probably began retreating some time after 10.2 ka BP.

A double glacier maximum is indicated by the beds of gyttja clay in the upper part of the glaciolacustrine Younger Dryas sediments in lake Svarttjørn and lake Holatjørn. Likewise, many of the Younger Dryas cirque moraines in this region consist of two parallel ridge systems. At Kråkenes, too, there is a minor end moraine proximal to the main ridge (Larsen & Longva 1979). Furthermore, Stalsberg (1995), based on sedimentological criteria, argues for a mid Younger Dryas warming – during which the Vedde Ash was deposited – characterized by large meltwater discharge and open lake water during the summers. Although the inferred warmer intervals at Svarttjørn and Holatjørn seem to have occurred after the ash fall, we cannot exclude the same climatic forcing as at Kråkenes, because, at these two sites, contrary to that at Kråkenes, time-lags have to be expected between the supposed climatic shifts and the build-up and waning of the ice lakes.

The behaviour of the inland ice is not the subject of this investigation. However, the stratigraphy at the reference basin lake Teigetjørna is worth mentioning. According to our interpretation, traces of a fjord glacier readvance, which could be related to the Vardehaug substage, are recorded immediately beneath the Vedde Ash layer. The age estimate of the Vardehaug moraines is 10.6–10.7 ka BP (Mangerud et al. 1984; Klakegg & Nordahl-Olsen 1985; Andersen et al. 1995; Aarseth et al. 1997), and the age of the marked Nor moraines east of Nordfjordeid is 10.5–10.0 ka BP (Mangerud 1980; Klakegg & Nordahl-Olsen 1985; Fareth 1987). Our results imply that the age of the Vardehaug moraines is ca. 10.3 ka BP and the Nor moraines necessarily somewhat younger. However, the age estimates of the Vardehaug and Nor stages are based on marine shells, and if we take into account a 300–400 year higher apparent age during the Younger Dryas than during the Holocene (Bard et al. 1994), the marine data also support a late Younger Dryas Vardehaug readvance (Fig. 6).

To sum up, the main results of this investigation are:

– A greater expansion of the main Younger Dryas Ålfotbreen glacier than previously published is suggested towards the south and north, and a more restricted extension towards the east.
– A separate Younger Dryas ice cap complex existed in the Davik mountains. This glacier had outlets towards Elde, Davik and Dombestein. To the west of Ålfotfjorden, parts of the two ice caps probably coalesced. A cirque glacier probably occupied the Blålivatnet basin in Leirgulen during Younger Dryas.
– The mean Younger Dryas lowering of the equilibrium line altitude relative to the present mean ELA was ca. 580 m.
– Ålfotbreen reached its maximum during the middle Younger Dryas, well before the Vedde Ash was deposited (i.e before ca. 10.3 ka BP), indicating that the glacier probably was quite extensive during the Allerød interstadial s.l. too.
– Although somewhat weak, there are stratigraphical arguments for a double Younger Dryas glacier maximum, of which the second maximum occurred after the Vedde Ash fall.
– Large amounts of Vedde Ash shards have been found in glaciolacustrine sediments in lake Djupedalsvatnet, which is postulated to have been completely ice covered during Younger Dryas. We suggest that the ash grains were

temporarily stored in the glacier and transported into the lake by glacial meltwater some hundred years after the primary ash fall.

– The 'early' Younger Dryas readvance of the inland ice sheet in Nordfjord, the Vardehaug substage, might have terminated contemporaneously with the Vedde Ash fall (10.3 ka BP). If so, the Nor moraines turn out to be from the very end of the Younger Dryas. A possible surge mechanism involved during the Vardehaug glacier advance is suggested, due to a seemingly very low surface gradient of the fjord glacier during that time.

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